THE DESIGN AND PERFORMANCE

OF A STAND-ALONE SOLAR AND WIND POWERED

RTM HOUSE

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ABSTRACT

This research project investigates the viability of using renewable energy sources and passive solar design in Saskatchewan, with its harsh climate, abundant energy resources, and absence of financial incentives for residential renewable energy systems.

An experimental Ready-To-Move (RTM) house, using passive solar design and stand-alone solar and wind power with gas generator backup, was designed and built and has been tested for a one year period from January to December, 2006.

The design methodology was based on well established design procedures for passive solar homes and renewable energy systems that are documented in the literature. A data collection system was used to record solar and wind charging currents, and battery status and temperature data was recorded on a daily basis. Average household loads were estimated from this data.

For 2006, the power generation of the solar array was 990 kWh, which was better than the expected output of 927 kWh. However, the wind generator produced only 475 kWh, which was substantially less the expected output of 1430 kWh. Average wind speeds were lower than the normal for 2006 and power production was less than the manufacturer's projections for the specified wind speeds. Financial analysis showed that the lack of incentives and net metering made an off-grid system economically feasible only in remote locations where the cost of grid connection is over $20,000.

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I would especially like to thank my husband, Bill Campbell, not only for his constant support for my ideas and endeavors but also, as a journeyman carpenter, building the experimental house with my assistance. Also, a heartfelt thank you for all the help and support that I have received from family and friends who were interested in my project.

DEDICATION

This thesis is dedicated to my husband, Bill Campbell. He shared my enthusiasm for designing and building a solar home, the many hours of hard work to make the project a reality, and my joy at its successful completion.

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ABBREVIATIONS

AH, AHr	Amp hours
DOD	Depth of Discharge (for batteries)
GHG	Greenhouse Gas
MEPS	Minimum Energy Performance Standards
MPPT	Maximum Power Point Tracking
NRCan	Natural Resources Canada
RTM	Ready-To-Move
PWM	Pulse Width Modulation

1 INTRODUCTION

Many homeowners today are concerned about pollution, greenhouse gas emissions and dwindling fossil fuels. A growing number of people in Saskatchewan would like to own sustainable and environmentally responsible homes. They would like to be able to promote sustainability and to leave resources for future generations. But while interested in using the clean and renewable resources of solar and wind power, most people are unfamiliar with the design, operation and feasibility of such a system. Designing an energy efficient house that can operate as a stand-alone, solar and wind powered, system is complex. It usually requires extensive research and design on the part of the homeowner, or the coordination of various architectural and engineering design groups.   The design process is time consuming and can be expensive, providing a daunting barrier to most homeowners considering such a system. Many Saskatchewan homeowners would welcome a complete, easy to use, and affordable home package that incorporates energy efficient building design with renewable energy sources.

1.1 Energy from the Sun

What is a solar home? The term has been widely adopted to describe a house that employs appropriate design principles and advanced technology to utilize the clean and abundant energy from the sun. Energy from the sun can provide heat and electricity for residential and other building projects.

Heat from the sun's rays can be captured directly with passive solar building design. Passive solar design uses south facing windows with an appropriately sized overhang to collect the sun's heat in the winter and keep the house shaded and cool in the summer. Materials such as concrete, stone and tiles are often used on floors or walls as "thermal mass" to hold the heat overnight and moderate the temperature during the day. Thermal energy from the sun can also be used to heat a fluid in a solar thermal collector that then transfers the heat to be stored in a hot water tank where it can be used for domestic hot water and for space heating.

Light from the sun can also be converted to electricity by photovoltaic cells. Wind power from wind generators is also an indirect form of solar energy since wind results from differential heating of the earth's surface by the sun.

1.2 Solar and Wind Power Systems

Solar and wind power systems with battery storage are widely used as stand-alone systems in remote locations where it is difficult and costly to bring in regular grid power. There is a growing interest in using these systems in areas that are near grid connections, but where the cost of connection to the SaskPower utility starts at about $10,000.

Figure 1.1 shows a basic off-grid solar and wind power system. Deep cycle batteries store dc electrical current produced by a wind turbine and a solar panel array.

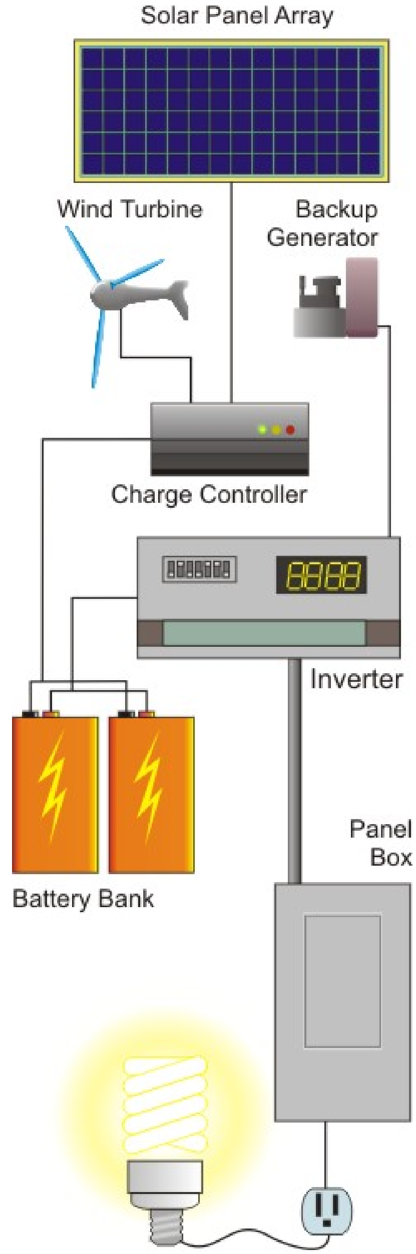


Figure 1.1 Off-grid Solar and Wind Power System with Battery Storage

A charge controller blocks reverse current and prevents overcharging of the batteries. An inverter converts low voltage dc power to 110V ac power to operate household loads. Inverters are available with modified sine wave output or pure sine wave output, depending on the needs of the application.

1.3 Passive Solar Home Design

The cost of an off-grid solar power system can be greatly reduced through careful design. A knowledgeable designer can design a house that provides natural lighting to reduce the need for electric lights, and uses passive solar design to reduce power requirements for household heating.

Passive solar design is the most cost effective way to use the sun's energy since there are very few, if any, additional construction costs. The method uses intelligent decisions at the building design stage to make effective use of the sunshine entering the home. Houses are oriented with a south-facing wall of windows that maximize solar gain during the winter and have suitable overhangs to minimize the solar gain in the summer. If the south window area is large in proportion to the floor area of the house, a thermal mass such as a concrete floor or stone wall can be used to absorb some of the heat during the day and radiate the heat at night. This design technique incorporates passive solar heating, passive cooling and natural day lighting in a unified design that reduces energy needs for heating in the winter, cooling in the summer and artificial lighting.

1.4 Benefits of Solar Power

Small, self-contained residential systems give the homeowner control over his or her power usage and costs. The energy is clean, free and renewable. Table 1.2 lists some of the benefits of solar power and their significance.

Table 1.2 Benefits of Solar Power (taken from[12])

The Benefits	Why They Are Important
Solar produces power during periods of peak energy demand.	Peak shaving reduces the cost of generation and reduces stress on transmission lines.
Few “Not in My Back Yard” concerns – the only energy source which does not require an environmental assessment.	A rapid installation time reduces forecasting risks.
Solar power is generated on the site of energy usage.	Avoids line losses, line upgrades and infrastructure costs.
Costs are in the initial purchase price of the equipment – there are no energy costs.	Provides stability to energy price forecasts. Reduces reliance on fuels that may fluctuate in price.
Local energy production reduces reliance on imported energy and long distance transmission.	Keeps local energy dollars in the community. Creates jobs in every region of Canada.
It produces local energy, autonomous from conventional energy supply.	Reduces disruption of energy due to natural or geo-political events.
Direct and lasting contribution to reduction of CO_2 and other emissions.	Reduces environmental costs caused by the use and transportation of fossil fuels.

1.5 Barriers to the use of Solar Energy in Saskatchewan

The use of solar energy in Saskatchewan faces a number of obstacles including lack of consumer knowledge, relatively low energy costs compared to other countries, and no incentive programs to promote the use of renewable fuels.

Most Saskatchewan homeowners are either totally unaware of the potential of solar energy or are aware of the concept but have very little information or understanding of how solar energy systems work. This became very obvious when I promoted public awareness of the solar principles used for the experimental house by conducting an open house, numerous tours, and answering many phone and email inquiries. It is amazing how few people know about passive solar house design, considering that this involves little or no extra cost – just energy smart design at the outset. The idea of using solar panels seems to be more widely known but many people do not understand what they do, thinking that photovoltaic panels keep your house warm and are surprised to find out that they provide electricity, not heat. The next misconception is that you can use solar power to heat your home with electric baseboard heaters or by running geothermal heat pumps. Neither of these options is practical because of the enormous amount of power that is needed to adequately heat the home. Solar thermal energy, which captures solar heat directly using a heat transfer fluid such as glycol, is a more efficient way to provide home heating using solar energy.

Few people know that power usage determines the size and cost of the system, or realize that energy storage and conversion are a necessary part of the process. I have had many inquiries from people who would like to put a few solar panels or a wind generator on their roof and thus save money on their power bill. They are surprised at the cost of setting up a basic system, since the power must be converted to 110 V or preferably 220 V. Unfortunately, the savings on their electrical bill, especially if they do not practice energy conservation, may not be very noticeable due to the relatively low cost of purchased electrical power. This is very unfortunate because many people have expressed an interest in doing such a grid-intertied system – a system which is very common in various countries, such as the United States and Germany, where this option is made feasible through programs such as net metering, feed-in tariffs, or rebates or interest free loans on the purchase of the equipment.

Net metering pays the homeowner for any excess electricity produced by the solar power system. Payment is at the same rate as the homeowner is charged for the electricity purchased from the utility when the solar power system is not producing enough power to meet the needs of the household. This is a very practical system that requires only one meter and provides both an effective backup for the solar power system and makes good use of the extra power instead of wasting it by diverting it to some type of dump load.

Feed-in tariffs are similar to net metering but pay the homeowner at a higher rate than is charged for the power drawn from the electrical utility. This method is usually used for the first few years before net metering is implemented and is meant to serve as an incentive for homeowners to buy solar energy systems. On March 21, the Ontario government announced its "Standard Offer Contract" which will pay individual owners of solar power equipment, such as homeowners, $0.42 per kWh for the electricity that they sell back to the utility. This makes Ontario the first province in Canada to have such a program. The practice is very common in many states in the United States and in European countries such as Germany.

Rebates or interest free loans are another form of incentive that is usually coupled with feed-in tariffs or net metering to promote the development of renewable energy resources. Unfortunately, Saskatchewan does not provide any of these incentives. SaskPower will actually buy power from a solar power producer but at a rate much lower than that charged for purchased power. Currently the buyback rate is about $0.03 per kWh and there are many regulations that must be met when the system is installed. Since the differential rate requires the installation of a second meter, with its attendant rental costs, this is not a cost effective use for solar power.

Government and utility policies in Saskatchewan limit the practical use of small residential solar and wind power systems to rural and remote locations, so they are almost never used in urban sites, except as demonstration projects.

1.6 Research Objectives

This research project originated from the author's interest in building a home using renewable energy sources as much as possible. The intention was to use solar and wind energy for power and passive solar design for heat gain, with underground construction for heat retention and insulation value. A design for an earth-sheltered home was developed but it quickly became obvious that the construction of such a building was very expensive and not easily modifiable if the design turned out to be less than optimal. Rather than proceed with this untested design, I designed a small experimental house using somewhat more conventional ideas. I modeled it on a conventional style of home and added some passive solar heating and a stand-alone solar and wind power system with battery storage. The power system included fossil fuel backup. The experimental house was designed as a Ready-To-Move (RTM) house so that it could be moved off the property after testing. With input from this experiment, a permanent energy-efficient home will be built on the property.

The design of the RTM house and power system was based on existing literature on passive solar and solar and wind power systems. The house was constructed and the systems put into commission over a two year period. The house has been operating quite successfully and could be used as a prototype design for Saskatchewan RTM solar homes.

This research project was initiated after the house was designed and built. The purpose of this research is to evaluate the electrical performance of the experimental house and develop appropriate design methods and procedures for self-sufficient RTM energy efficient passive solar homes with stand-alone solar power and battery storage, and optional wind power.

2 TECHNIQUES FOR SOLAR HOME DESIGN AND EVALUATION

A solar powered home presents a unique set of challenges for the designer. The home relies for its power on environmental conditions, which are highly variable from site to site and even from year to year at any particular site. Achieving a reliable system design under these conditions can be costly and may not be cost effective where inexpensive grid power is readily available.

Many engineers, scientists and homeowners have tackled these challenges to provide effective designs for their applications and geographic location. Solar power system design must take into account the solar radiation that is available at a particular site and the power needs of the consumer. If wind resources are good, a wind generator may also be an option.

Passive solar home design is the most cost effective way to provide a substantial portion of a building's heating requirements. The design method has been investigated extensively and guidelines are well established.

The energy savings and environmental benefits of solar power and passive solar design have been demonstrated and proven through extensive research and examples. In a year, a 2 kW solar array produces 2.5 – 3.6 MWh per year resulting in energy savings of 20 – 30% and greenhouse gas (GHG) emissions reductions of 0.7 – 3.6 tonnes (depending on the fuel used for electrical generation). Similarly, a typical Canadian passive solar home will have an energy savings of 5 – 30% over a standard home, and will reduce GHG emissions by 0.9 – 7.3 tonnes/year[14].

2.1 Passive Solar Design

Passive solar home design is not a new concept. For as long as people have built homes, they have used the sunshine entering through the windows as a source of light and heat. Much has been written about passive solar design in the last few decades and there are several available computer programs to assist in designing and analyzing passive solar design features.

2.1.1 Basic Guidelines for Passive Solar Design

Passive solar design makes effective use of building shape and orientation, distribution of window glass and overhangs, and heat absorbing materials. Some general guidelines for the northern hemisphere are[12]:

Building Layout and Orientation:

- The longest wall of the house should be oriented within 10 degrees of true south.
- Jogs, offsets and other projections should be minimized on the south wall, but porches and garages are useful on east, west and north walls for shading and insulation value.

Window Glass and Overhangs:

- To maximize solar heat gain and minimize thermal losses, window glass should be distributed as (building code regulations permitting):

- South-facing Glass: 5% to 12% of the floor area of the house.
- East-facing Glass: less than 4% of the floor area.
- West-facing Glass: less than 2% of the floor area (to avoid overheating in the summer).
- North-facing Glass: less than 4% of the floor area.

- Windows on the east and west sides of the house do not receive much solar radiation during the winter months, so they are a source of heat loss rather than heat gain. In the summer, they are very difficult to shade so are an unwanted source of heat gain. However, windows are still desirable on these walls because they admit light to the rooms, provide more attractive house design and views in these directions, and operating windows assist with the natural cooling of the house in summer months.
- Overhangs should not cast shade on south-facing windows on the winter solstice (December 21) and should completely shade these windows on the summer solstice (June 21).

Heat Absorbing Materials for Thermal Mass:

- Thermal mass such as concrete or tile floors and brick or stone facings are used to absorb solar heat during the day and reradiate it at night. Although the mass of the house itself (drywall, floors, cabinets, etc.) provides some thermal mass more may be recommended.
    - If the south-facing glass is more than 7% of the floor area thermal mass should be added for the area of glass that is greater the 7%.

- In general, the maximum amount of floor mass that should be used is 1.5 times the area of south glass (assuming a thickness of 4” for the thermal mass). If more thermal mass is needed it can be added to the walls.
- The recommended thickness for thermal mass is 2” to 4”. It has been shown that thicknesses greater than 4” do not contribute significantly to heat storage. For example, a six-inch mass floor can only perform about eight percent better than a four-inch floor.[12]

Energy savings of up to 80% are possible with the use of energy efficient, high solar gain windows and appropriate insulation for the climate conditions. The selection of windows is a tradeoff between achieving high solar gain and a high R value (insulation factor) to prevent heat losses during the night. Window coverings can reduce nighttime heat losses by up to 30%.

2.1.2 Energy Analysis of Passive Solar Designs

Energy analysis is generally done using one of the many computer programs that are available for this purpose. Some commonly used programs are RETScreen International, BGW 2004, ResCheck and Home Energy Saver.

RETScreen International was developed by Natural Resources Canada, is managed by CETC-Varennes, and is available free for download. It provides energy, cost and Greenhouse Gas analysis for Renewable Energy Technology projects. The steps in the Standard Analysis are shown in Figure 2.1.

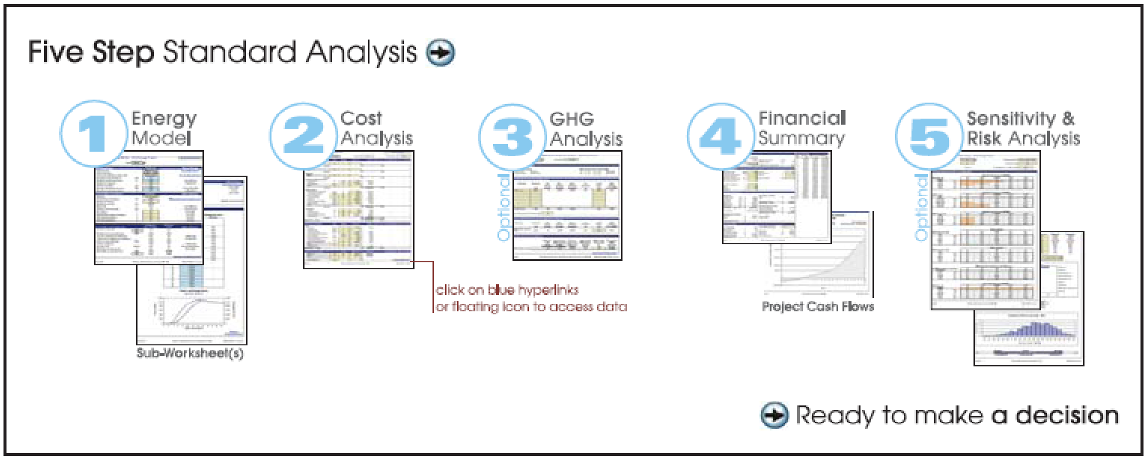


Figure 2.1 RETScreen International Standard Analysis

Natural Resources Canada (NRCan) was created on January 12, 1995 by merging Energy, Mines and Resources with Forestry Canada. Today NRCan employs about 4,200 people and has a budget of $812 million (2003-04). It is one of the largest science-based departments in the Government of Canada, specializing in the sustainable development and use of natural resources - energy, minerals and metals, forests - and earth sciences.

BGW 2004 is Windows based software developed by architect Fred Roberts and is a user-friendly program that allows quick analysis and comparisons of various options during the development of the design. It is useful for deciding on amount of south glass, thermal mass and insulation for an optimal design.

REScheck was developed by the U.S. Department of Energy's Building Energy Code program and was designed to be used with their building codes.

2.2 Design of Stand Alone Solar and Wind Power Systems

A stand-alone residential renewable power system consists of five basic components:

1. An energy generation system, consisting of a solar panel array or a wind generator or both.
2. An energy storage system, generally a bank of deep cycle lead-acid batteries.
3. A charge control system, to prevent overcharging of the batteries.
4. An inverter to convert low voltage dc to 110 V ac to power normal household loads.
5. A backup generator operating on gasoline, diesel, natural gas or propane.

The effectiveness of the total system depends on the availability of solar radiation and the wind speed distribution at the proposed building site and the load requirements of the home. The energy storage system should provide the power needs of the house for a specific number of days when no charging source is available (days of autonomy). The charging system must be able to satisfy the building's loads and recharge the batteries, based on available solar radiation and wind resources.

2.2.1 System Components

2.2.1.1 Solar Power Generation

The process of converting solar energy to electrical energy is called photovoltaic power generation. The photovoltaic cell (or solar cell) was invented in the early 1950s, with the increase in semiconductor technology. Photovoltaic panels are made from silicon -

either a single crystal, amorphous crystals, or a thin film. Considerable research is being done to find other materials, such as organic materials, that would be suitable. When sunlight strikes the surface of the semiconductor, it transfers energy to some of the electrons so that they are no longer bound to the nucleus and are free to move through the material. By connecting wires to the panel you can use this current of free electrons to do work on an outside circuit.

Solar panels are specified by the open circuit voltage and short circuit current, and the Operating Point – also called the Maximum Power Point. This point can be determined experimentally by recording the current and voltage of the panel for various values of resistance, calculating the resulting power, and graphing it versus the voltage. The peak of the graph is the Maximum Power Point, or operating point, of the panel at which it operates the loads most efficiently.

There are three common manufacturing methods for solar cells. The manufacture of monocrystalline cells is the most expensive. They are cut from a single silicon crystal and are the most efficient method, typically about 15%. Multicrystalline cells are produced by casting molten silicon into ingots, then cutting them into thin wafers. This is a less expensive method but is also less efficient, typically 12 %. Flexible solar panels are produced by a thin film manufacturing process in which single atoms are deposited on a base. This is considerably less expensive, but also much less efficient, at around 6%. Thin film panels also tend to degrade and have a shorter lifetime than crystalline cells.

Photovoltaic cells have been criticized as taking more power to produce than they will generate in their lifetime. However, a study by K. Knapp and T. Jester shows that photovoltaic panels recoup their production energy in two to four years, while their expected lifetime is in excess of twenty-five years [24].

2.2.1.2 Wind Power Generation

Wind generators varying in power output from 100 W to several kW are common components in residential renewable power systems. The energy that can be produced by a wind generator depends primarily on the average wind speed and the wind speed distribution at the site, and on the swept area of the wind generator rotor blades.

The power output of a wind generator varies directly with the blade swept area, so double the swept area will yield roughly double the power. However, the wind speed has a cubic relationship to the power output. The power of the wind passing through a circular area is given by [32]:

$$P = \frac{1}{2}\rho v^3 \pi r^2 \tag{2.1}$$

where P = the power of the wind measured in W (Watt).
ρ = density of dry air (1.225 kg/m^3 at average atmospheric pressure at sea level at 15° C).
v = the velocity of the wind measured in m/s
r = the radius of the rotor measured in m

Only a fraction of this kinetic power in the wind can be converted to mechanical power using a wind turbine. Betz' law shows that the maximum power that can be converted is less than 59% for any wind turbine since, if a rotor were 100% efficient, it would stop the wind [32]. Typical conversion efficiencies for wind turbine rotors are 35% to 45%. Allowing for losses in the rotor, transmission generator and other components in the wind energy system further reduces this to 10% to 30% [36].

The energy that can be expected from a wind generator over time depends on the distribution of wind speeds, which is generally shown as a probability density function and this approximates the Rayleigh Distribution[32].

Wind generators have a cut-in wind speed below which no power is produced, a rated wind speed at which maximum power is produced and a maximum speed above which the generator would sustain damage, so it is either shut down or turned partially out of the wind for protection.

2.2.1.3 Batteries

The most common type of battery used for residential applications is the flooded lead-acid deep-cycle battery. The battery consists of a positive plate of lead dioxide, which is the active material, and a high surface area lead negative plate. They are immersed in an electrolyte of sulphuric acid solution. Batteries designed for solar power systems have thicker plates than automotive batteries so that they can be operated at a deeper Depth Of Discharge (DOD), typically 50%.

Battery capacity for solar applications is rated in Amp Hours (AH), which is the current in amps multiplied by the number of hours that the current is flowing. The capacity is not the same for all conditions. It depends on the temperature, the discharge rate, and the end voltage to which it is discharged. The batteries are usually rated at the 20 hour rate and the 100 hour rate. The slower discharge rate yields a higher capacity. In solar applications the demand, and therefore the battery discharge rate, is usually quite slow, so the 100 hour rate more closely approximates the actual capacity of the battery.

Batteries should be fully charged fairly frequently and should not be discharged for extended periods or a condition called sulphation will occur and a higher voltage equalization charge will have to be applied to the battery to reverse the sulphation of the plates.

Many power system designers size the battery banks to provide for the household power needs for approximately three days with no charging if the charging system is purely solar, or for five days if the system is primarily a wind charging system.

2.2.1.4 Charge Controllers

Charge controllers are essential to protect the batteries from overcharging. They block reverse current that would discharge the batteries into the solar panels at night, but their main function is to prevent battery overcharge. If more charge is applied to a battery that is already fully charged it will separate the hydrogen and oxygen and “boil” off the gas. This can cause overheating and degrade the battery.

Some controllers regulate the charge to the battery by simply switching the current totally on or totally off – ON/OFF Control. Others reduce the flow of current gradually. This is called pulse width modulation (PWM) and holds the voltage more constant.

A more sophisticated method that has been introduced in the last few years in a number of charge controllers is Maximum Power Point Tracking (MPPT). This device "tracks" the maximum power point of the panel.

Often, charge controllers will also have a low voltage disconnect that disconnects the load if the batteries reach a specified low voltage set point. Many charge controllers also feature displays to monitor battery status, voltage, and current.

2.2.1.5 Inverters

Inverters convert low voltage dc power to higher voltage standard household 110 vac power. Major improvements in inverter technology have greatly improved the viability of residential solar power systems because it allows the homeowner to operate regular household appliances. The inverter is generally wired directly into the main household distribution panel, so the technology is invisible in daily life.

Modern sine wave inverters used for residential applications typically have efficiencies of 90 – 95 per cent. They can be programmed to automatically start a backup generator, with options such as quiet times during which the generator is not allowed to run or exercise times when the generator is run for maintenance purposes. Grid-tie inverters can be programmed to connect to grid power to supplement renewable energy power production or to sell power back to the utility when the RE system produces more power than is needed.

2.2.2 Solar and Wind Resource Assessment

As solar and wind power become more widely used, there is a growing need for good quality weather data to provide the basis for sizing solar arrays and battery banks, and determining the appropriate size of wind generator for the power system site. Hourly weather data are also often used in computer simulations to assess the potential performance of small photovoltaic-wind energy systems.

The ideal situation is where weather stations are operating close to the proposed site and data is available for several years. This provides information for design and analysis of renewable energy systems, including average climate values over an extended period, distribution patterns of solar radiation and wind speeds, and standard deviations as well as defining extended periods of low sun or calm winds. However, solar and wind power systems are most commonly used in remote sites, where such data is not readily available.

To address the problem, a very useful data base was established by NASA Surface meteorology and Solar Energy (SSE) to provide many kinds of weather and climate information to assist the designer of Renewable Energy Technology (RET) projects [3]. The SSE data set provides satellite data, for solar insolation and meteorology that is continuous around the globe on a 1º x 1º grid system. Parameters such as the average monthly radiation at various tilt angles, diffuse and direct radiation, clearness index, number of no sun days, and wind speeds for various heights and vegetation types are determined for each grid square, using a number of methodologies described in their Methodology document [17]. This information is available for a ten year period from July 1, 1983 to June 30, 1993. The database is available on the Internet [3] and is searchable for every latitude and longitude, in one degree increments.

The weather data enables the designer to determine the amount of solar radiation incident on a square meter of solar cells as a monthly or yearly average, and also provides minimum and maximum values over the ten year period. Wind data aids in choosing an appropriate size of wind generator for the given wind speed distribution pattern.

2.2.3 Load Analysis

The size of the solar power system depends on how much power is needed to operate the various systems and appliances in the home. Loads can be continuous (running 24 hours a day) or intermittent. Many large loads, such as toasters, vacuum cleaners, washing machines and microwaves are not used often or are only used for very short time periods. On the other hand, small loads can contribute significantly to the overall load if they are a continuous draw. Small loads that are not obvious to the homeowner, because devices and appliances appear to be shut off but are still drawing power for quick power up, are generally referred to as “phantom loads” and are easily overlooked when calculating load requirements. Examples of phantom loads include televisions and DVD players that can be operated with remote controls. These loads can be mostly eliminated by installing switch controlled outlets or a switched power bar that turns off the appliances when not in use.

2.2.3.1 Energy Efficiency Measures

The most important principle for designing a home with a solar power system is very aptly stated by Richard Perez, editor of Home Power magazine: "Every watt not used is a watt that doesn't have to be produced, processed, or stored"[18]. This is a concept that is seldom considered by homeowners using grid power, but is essential for anyone who wants to live in an off-grid home.

Energy efficiency is the best way to make the system more cost effective, but this does not mean doing without the customary appliances and conveniences. Many of the major appliances that we commonly use have become much more energy efficient over the last decade as both government and consumers became more aware of the importance of energy efficient appliances.

One of the developments that has made solar power feasible is the introduction of the 1992 *Energy Efficiency Act.* The Energy Efficiency Regulations authorized by this act ensure that new appliances imported into Canada, or manufactured in Canada and shipped from one province or territory to another, comply with federal minimum energy performance standards (MEPS).

A study was done by the Office of Energy Efficiency to assess the energy savings as a result of the MEPS between 1992 and 2001. Their findings showed an impressive energy saving. “Since the energy saved in any given year accrues over time, cumulative energy savings grew steadily between 1992 and 2001. They reached a total savings of 14.02 PJ in 2001, the equivalent of a year's energy for about 126 000 Canadian households.” [4]

The Energy Use Data Handbook, published by the government of Canada, lists the energy usage of various major appliances from 1990 to 2003. As shown in Table 2.1, the improvements are dramatic.

Table 2.1 Residential Appliance Unit Energy Consumption (UEC) (taken from [6])

	1990	**2003**	**Total Growth**
UEC[1] for new electric appliances (kWh/year)			
Refrigerator	956	487	-49.1%
Freezer	714	369	-48.3%
Dishwasher[2]	101	52	-48.9%
Clothes Washer[2]	97	57	-41.8%
Clothes Dryer	1,103	914	-17.1%
Range	772	718	-7.0%

1) Unit energy consumption is based on rated efficiency.
2) Excludes hot water requirements.

Not only have improvements been made in the efficiency of appliances produced, but sales of major appliances also show that consumers are buying more energy efficient appliances. The Office of Energy Efficiency reports:

> “Refrigerators are becoming more efficient, thanks largely to the ongoing efforts of manufacturers and the MEPS. From 1990 to 2001, the market share of refrigerators requiring less than 50 kWh per cu. ft. per year increased from 5.4 to 91.7 percent.

The greatest increase in market share was for refrigerators that used less than 30 kWh per cu. ft. per year. There were very few refrigerators in this range of energy consumption in 1990, but they became the dominant model in 2001, accounting for 44.5 percent of the market.

In 1990, refrigerators requiring at least 50 kWh per cu. ft. per year dominated the market, accounting for 94.6 percent of units shipped on the market. Since 1993, in a dramatic shift, the majority of the refrigerators have required less than 50 kWh per cu. ft. per year." [4]

The cumulative energy savings resulting from these improvements and the changing patterns of consumer purchases is shown in Figure 2.2. Since every house has at least one refrigerator and it is usually one of the major power draws in the house, this improvement, which essentially cuts the power usage of the refrigerator in half, goes a long way towards making solar power systems more cost effective.

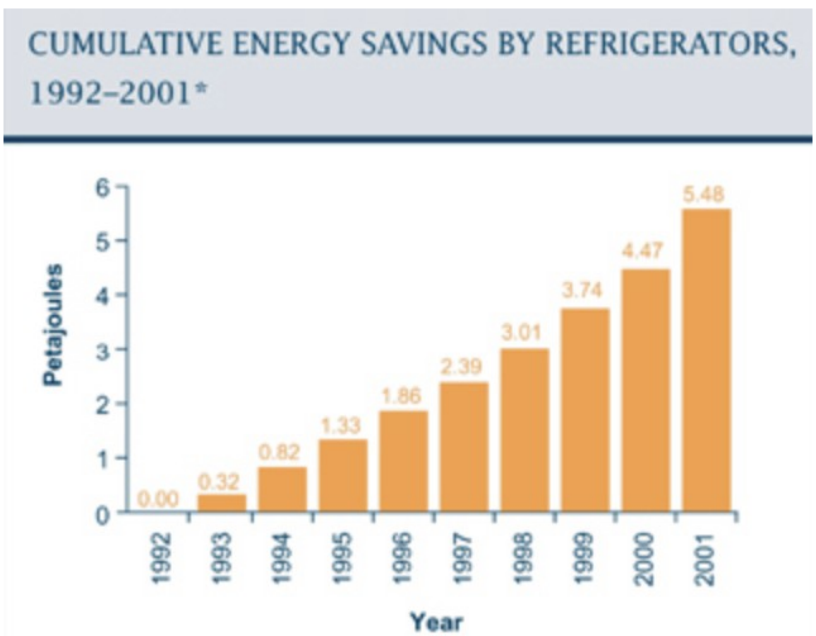


Figure 2.2 Cumulative Energy Savings from Efficiency Improvements for Refrigerators (taken from [4])

The drive for energy efficiency has also been proceeding in other areas. The development of the compact fluorescent light bulb was a major step forward, since incandescent lighting was notorious for high energy usage. Now, LED lighting is making strides in reliability, brightness and affordability at a much lower power rating. The same light output can now be achieved for about one tenth of the power needed for incandescent lighting.

2.2.3.2 Typical Loads for a Renewable Energy Powered Home

Renewable power systems are used throughout the world to operate many common household appliances and tools, but are generally never used for space heating because of the highly inefficient energy conversion process. For the same reason, gas stoves are usually chosen over electric ranges and ovens for cooking. Other appliances with high energy requirements, such as coffee makers and microwaves, are cost effective to use in a renewable energy system, however, since they are operated for only short periods of time. Electric refrigerators are also more common than propane, because they have become quite energy efficient and so lend themselves well to this clean form of energy.

The types of appliances that are commonly used in a renewable energy system are shown in the results of a 2003 survey from the Yukon that asked 85 homeowners with off-grid main residences what appliances they normally used. It was found that, for the major appliances, the majority had refrigerators and washers, while fewer people had freezers and dryers, and dishwashers were the least common. Small appliances used were listed in order of popularity:

TV	78.8%
VCR	74.1
Stereo music system	70.6
Blender food processor	62.4
Radio	57.6
Block heater	56.5
Satellite dish	51.8
Printer	50.6
Iron	48.2
Desktop computer	45.9
Microwave	44.7
Toaster	43.5
Other small appliance	32.9
Other computer peripherals	27.1
Laptop computer	25.9
Clock radio	23.5
Clock	20.0
Coffee maker	20.0
Electric kettle	15.3
Can opener	8.2
None	5.9

- Tools and equipment used, in order of popularity are:

Small 120V electric hand tools	87.1
Cordless power tools	76.5
Large stationary power tools	70.6
Compressor	56.5
Welder	44.7
Heavy equipment	34.1
Other	9.4
None	7.1

An interesting finding was that 94% of those surveyed use their dwelling year-round, and 60% operated some kind of business from the property. [19]

2.3 Studies of Solar Energy and Energy Efficiency in Saskatchewan

In Saskatchewan, studies in the 1970s investigated the possibility of building solar homes as research projects to explore the viability of using solar energy for home power and heating. Unfortunately, the lack of good inverters and the inefficiency of most electric appliances coupled with the high cost of solar technology made solar power an unattractive option at the time. As technology improved and costs came down, the option was explored again more recently with the Advanced Houses Program.

The Advanced Houses program was launched in 1991 by Natural Resources Canada (NRCan) with the goal of building houses that incorporate energy efficiency and renewable energy sources to exceed previous house performance standards based on the R-2000 program. Ten houses were selected across Canada for the program and NRCan provided a portion of the funding and technical support [20].

The Saskatchewan Advanced House, one of the successful proposals, was built in Saskatoon in 1992, as a joint project by Carroll Homes and organizations such as SaskPower and the Saskatchewan Research Council. The Design Guidelines were to reduce the purchased energy requirement to half of the energy used by a typical R-2000 house. Standards had to be met for categories such as airtightness, ventilation, lighting per floor area, noise levels and environmental recommendations such as using EcoLogo products and recycled materials. The energy performance analysis of the houses was done using purchased energy converted to kWh.

The Saskatchewan Advanced House included a 1.9 kW photovoltaic system that provided 877 kWh of electricity during the first year of monitoring. This was used to power a high efficiency DC refrigerator and the HRV fan motors and battery room exhaust fan. The house also featured a solar domestic hot water system that used evacuated tube collectors and a large site-built tank [1]. An impressive data collection system was used to monitor all aspects of the house performance for a period of one year during which the house was unoccupied and available for public viewing, and then another year during which it was occupied by the purchasers of the house.

The energy performance results were very good in many of the categories that were monitored, but the results for electrical consumption were quite unexpected. The energy target set for the house was 20,514 kWh/yr. The actual usage during the year of occupied monitoring was 31,322 kWh. Part of the reason for this extra usage was that the first thing the occupants did when they moved in was to replace the efficient dc refrigerator with a large side by side refrigerator freezer that consumed 1037 kWh/yr. They also introduced a home theatre speaker system that used 1138 kWh/yr as well as other miscellaneous plug loads [1].

This demonstrates that educating the homeowner about suitable appliances to be used in an energy efficient home is just as important as providing an energy efficient design.

2.4 Predicting Performance of Small Solar and Wind Power Systems

Some interesting work has been done on predicting the performance of solar and wind power systems. Sukamongkol et. al. developed mathematical models for the various system components – PV array, battery, controller, inverter and some ac loads such as a refrigerator. The resulting simulation model was validated with an experimental system that was set up and tested under various climatic conditions. It was found that the model was in good agreement with the experimental results and the model provided a basis for analyzing PV system performance and array sizing [8].

Many performance studies of small solar energy systems have been done using simulated weather data. Producing such simulated data for solar radiation, wind speed and temperature has been the subject of numerous studies [16]. For example, hourly data can be generated for a monthly average day or a sample of three or four days that represent the solar radiation for a typical month. This can then be used in programs designed to evaluate a solar design based on such data.

Bagen, for his M.Sc. thesis at the University of Saskatchewan, has developed a sequential Monte Carlo simulation method for generating capacity adequacy evaluation of small solar and wind power systems [11]. His technique determines adequacy indices based on models of power generation, chronological loads and energy storage. His stochastic simulation method provides a practical analytical technique for the many variables in the renewable energy power system, a system that cannot be effectively analyzed with the traditional techniques used for conventional systems such as large power plants.

3 DESIGN SPECIFICATIONS AND CLIMATIC ENVIRONMENT

3.1 Design Specifications

The purpose of the experimental house is to serve as a test case and aid in the planning of a complete stand-alone, environmentally efficient, home package. Using the knowledge gained from the prototype, an affordable housing option that supports a convenient and comfortable lifestyle using renewable energy sources can be designed. One purpose of the project was to demonstrate that such a house can look and feel very much like a regular home, and can fulfill most of the same functions. The main criteria for the design were:

1. The house should be completely self-sufficient for power and heat, with no connections to standard utilities.
2. The systems should have a payback period of less than 15 years, assuming a rural connection cost of at approximately $10,000 for power and $2500 for natural gas.
3. The house should provide standard necessities and conveniences. This assumes an awareness of energy usage on the part of the consumer.
4. The system should safely operate standard 110 V loads and have a minimum three day battery storage capacity to provide good reliability at a reasonable cost.

To achieve this, the house was designed with the following specifications:

1. Cost Specification
    a. Basic house is the same cost as any standard home built to National Building Code standards
    b. Power system installed cost is approximately $30,000, which provides a reasonable payback period, assuming a $10,000 connection cost.
2. Power System Specification
    a. Stand alone power system – no grid connection
    b. Solar and wind charging systems
    c. Battery storage
    d. Generator backup
    e. Power to support the use of the normal complement of household appliances, tools and office and entertainment equipment.
    f. Propane for cooking, hot water and backup heating.
3. Construction Specification
    a. Ready-to-Move construction
    b. Passive solar design
    c. Conforms to standard building code

The house should maximize the use of renewable solar and wind power sources. However, the purchase of such technology must be accessible to the average homeowner. The system should be sized to operate basic mechanical and lighting requirements for a house and the basic complement of appliances to which a 2 to 4 person family would be accustomed. The purchase and installation cost should be no more than $30,000. It is assumed that the cost to connect to the electrical power grid would be $10,000 or more. At the rural location of the experimental house, a typical connection to the power grid costs approximately $10,000, even though this is not a remote site. Power is available about 200 meters away.

The maximum solar power installation cost of $30,000 was chosen because this gives a payback period of less than 15 years, which is well within the expected lifetime of the equipment – typically about twenty to twenty-five years. Calculation of the exact payback period is more complex and depends on factors such as the cost of the grid connection at the proposed site, maintenance costs, return on investment comparisons and environmental benefits.

Although many people are interested in protecting the environment and reducing greenhouse gas emissions, this must be within their means and show a reasonable return on investment. Since the capital costs of renewable energy systems are quite high, payback periods can be long without some form of assistance to the homeowner, such as rebates, feed-in tariffs or low interest loans. Many countries provide such assistance in order to promote environmentally responsible energy choices. Unfortunately, there is no such program in place in Saskatchewan, so the entire capital cost must be borne by the homeowner, who must also finance the project at current interest rates.

The experimental house was designed to provide reasonable payback in the non-remote rural area in which it is located. As will be shown in the design calculations in Chapter 4, this dictated a maximum load of approximately 150 kWh/month or 1800 kWh/year. This is substantially lower than the electrical load of an average house, which typically uses at least five times this much energy.

Achieving this load constraint required some compromises and careful design, and it was a priority to avoid using dc or special order appliances. All large and small appliances and mechanical systems should be readily available locally and be similar to those used in standard homes.

3.2 Climatic Environment

The power output of a renewable energy system depends on the microclimate conditions at the project site. Climate data is available from the Climatological Reference Station, Saskatchewan Research Council, in Saskatoon, SK at lattitude 52°09’N, longitude 106°36’W. It is also available from the airport weather station and from the NASA Surface meteorology and Solar Energy (SSE) renewable energy resource website[3].

3.2.1 Climate Data for Sizing Solar Power Arrays

The power output of a solar array depends on the incoming solar radiation at the tilt angle of the array throughout the year. Solar radiation has two components, direct and diffuse radiation. Direct solar radiation reaches the earth’s surface without scattering or reflection. Diffuse solar radiation is radiation that is scattered in the atmosphere and from objects and surfaces on the ground. The sum of these two is generally called "global solar radiation" on a horizontal surface.

The SRC Climatological Reference Station provides global solar radiation climate normals for the Saskatoon area for the period from 1961 to 1990.

The NASA SSE website provides global insolation and meteorology data for all points on the globe on a 1° x 1° grid for a ten year period from July, 1983 to June, 1993. The data were obtained from the NASA Earth Science Enterprise (ESE) program's satellite and re-analysis research data and additional data were estimated and validated using several analysis methods[3]. The website gives average monthly values for radiation incident on a horizontal surface and also calculates the average radiation on a tilted surface pointed at the equator (i.e. pointed south in the northern hemisphere and north in the southern hemisphere), for several common tilt angles and for the optimum tilt angle. Table 3.1 shows solar radiation data for the grid square from latitude 51º to 52º and longitude 106º and 107º in which the experimental home is located.

This table shows a number of parameters besides the global solar radiation data. In the first row, 'SSE HRZ' is the monthly average amount of insolation on a horizontal surface, averaged over a 10-year period (July 1983 – June 1993). The parameter 'K' is called the *Average Clearness Index* and is the fraction of the radiation at the top of the atmosphere that reaches the earth's surface. It is averaged for that month for the ten year period. ‘Erbs DIFF’ is the diffuse radiation which is measured by blocking the direct radiation from the sun with a shadow band or tracking disk. It derives its name from the researcher, Erbs, who developed the calculation method with his research group[3]. ‘RET DNR’ is the Direct Normal Radiation and is calculated using the method in the RETScreen software for Renewable Energy analysis [3]. The global radiation is then calculated for the five tilt angles listed, as well as the optimum angle for that month for that location.

Table 3.1 NASA SSE Data – Parameters for Sizing Solar Arrays (taken from [3])

Monthly Averaged Radiation Incident On An Equator-Pointed Tilted Surface / RETScreen Method (kWh/m^2/day)													
Lat 51 Lon 106	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
SSE HRZ	1.19	2.18	3.60	4.75	5.65	5.61	4.95	4.28	3.33	2.20	1.39	0.94	3.34
K	0.51	0.57	0.59	0.55	0.53	0.48	0.45	0.45	0.47	0.47	0.50	0.49	0.50
Erbs DIF	0.43	0.69	1.24	1.80	2.23	2.46	2.37	2.02	1.52	0.90	0.52	0.36	1.38
RET DNR	3.07	4.50	5.35	5.46	5.86	5.08	4.23	3.84	3.55	3.34	3.07	2.76	4.17
Tilt 0	1.16	2.15	3.56	4.73	5.67	5.63	4.97	4.25	3.27	2.15	1.34	0.93	3.32
Tilt 36	2.57	3.86	4.96	5.37	5.67	5.35	4.81	4.51	4.01	3.30	2.69	2.24	4.11
Tilt 51	2.92	4.22	5.11	5.19	5.23	4.84	4.38	4.26	3.99	3.50	3.02	2.58	4.10
Tilt 66	3.10	4.33	4.97	4.74	4.56	4.20	3.85	3.81	3.77	3.50	3.16	2.76	3.89
Tilt 90	2.99	3.97	4.20	3.62	3.25	2.92	2.73	2.83	3.05	3.10	3.00	2.70	3.19
OPT	3.12	4.33	5.11	5.38	5.86	5.71	5.07	4.56	4.03	3.52	3.17	2.79	4.38
OPT ANG	73.0	65.0	51.0	33.0	17.0	11.0	13.0	26.0	42.0	59.0	70.0	75.0	44.4

Solar radiation data is provided for average values over the ten year period and also for the minimum and maximum average values for that month over the ten year period. The radiation values are available for three different methods of calculation – the RETScreen Method, the Page Method and the Extended Page Method. These are described in detail in the Methodology section of the SSE website [3]. The RETScreen method was chosen for this analysis because it is compatible with the energy analysis software that may be used in future analysis.

Table 3.2 shows the SSE radiation data based on minimum average values for the ten year period. These values are used to size the solar array for the experimental house.

Table 3.2 SSE radiation Data for the Minimum Average Solar Radiation over the Ten Year Period (taken from [3])

Monthly Averaged Equivalent Sun Hours Radiation Incident On An Equator-pointed Tilted Surface / RETScreen Method (kWh/m²/day)													
Lat 51 Lon 106	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
SSE MIN	1.12	2.12	3.37	4.57	5.07	5.08	4.37	3.84	2.87	1.85	1.15	0.90	3.02
K	0.48	0.55	0.55	0.53	0.48	0.44	0.39	0.40	0.40	0.39	0.42	0.47	0.46
Erbs DIF	0.44	0.70	1.28	1.82	2.27	2.46	2.34	2.00	1.51	0.92	0.54	0.37	1.39
RET DNR	2.83	4.38	4.88	5.17	4.97	4.23	3.29	3.09	2.71	2.50	2.30	2.59	3.57
Tilt 0	1.09	2.09	3.34	4.55	5.09	5.10	4.39	3.81	2.82	1.80	1.11	0.89	3.01
Tilt 36	2.35	3.71	4.56	5.14	5.05	4.85	4.24	4.00	3.35	2.61	2.07	2.09	3.67
Tilt 51	2.66	4.05	4.68	4.96	4.67	4.37	3.86	3.77	3.31	2.73	2.29	2.41	3.64
Tilt 66	2.82	4.15	4.54	4.53	4.08	3.82	3.41	3.38	3.11	2.71	2.38	2.57	3.45
Tilt 90	2.71	3.81	3.83	3.46	2.94	2.68	2.44	2.52	2.51	2.38	2.24	2.51	2.83
OPT	2.83	4.15	4.68	5.15	5.24	5.16	4.46	4.05	3.35	2.74	2.38	2.60	3.90
OPT ANG	72.0	65.0	50.0	33.0	17.0	11.0	13.0	24.0	40.0	56.0	68.0	74.0	43.4

Table 3.3 compares the radiation data obtained from the SSE website with the radiation data from the SRC Climatological Reference Station. The table shows that the SRC data is between the MIN and MAX values from the SSE website for the six months between the spring and fall equinoxes and for February, but is a little lower than the SSE minimum value for five of the six winter months between the equinoxes.

Table 3.3 Comparison of Global Solar Radiation: SRC climate normals with SSE Minimum, Average and Maximum Horizontal Insolation (kWh/ m^2/day)

Month	SRC MJ/m^2	SRC kWh/ m^2/day	SSE MIN	SSE AVE	SSE MAX
January	129.9	1.16	1.12	1.19	1.27
February	210.1	2.08	2.12	2.18	2.27
March	362.4	3.25	3.37	3.60	3.76
April	492.2	4.56	4.57	4.75	4.95
May	586.3	5.25	5.07	5.65	6.23
June	638.7	5.91	5.08	5.61	5.93
July	633.5	5.68	4.37	4.95	5.74
August	529.0	4.74	3.84	4.28	4.8
September	351.8	3.26	2.87	3.33	3.96
October	239.1	2.14	1.85	2.20	2.49
November	123.7	1.11	1.15	1.39	1.49
December	95.2	.85	0.90	0.94	0.98

- Normals are based on data from 1961 to 1990

This reflects the difference in the method of data collection and estimation. The minimum SSE values were chosen for this analysis because they are more consistent with the local ground data and they provide tilt angle radiation values not available from the SRC station.

3.2.2 Parameters for Determining Battery Capacity Requirements

The average amount of solar radiation is useful for sizing solar arrays but has only limited application for sizing the battery bank – the energy storage system. The parameters that are important here are the number of consecutive days with insufficient solar radiation to operate the load and charge the batteries. The SSE website provides parameters to assist with the sizing of the energy storage system. They are:

- *Minimum available insolation over a consecutive-day period.* This is given for 1, 3, 7, 14 or 21 day periods as well as the complete month. The value is given as a percent of the expected average kWh/m^2 value over the same consecutive-day period.

- *Solar radiation deficits below expected values incident on a horizontal surface over a consecutive-day period*. This is given in kWh/m^2 for the period.
- *Equivalent number of NO-SUN or BLACK days*. This is what must be supplied by the battery system and is given in the number of days.

Tables 3.4, 3.5 and 3.6 show these parameters for the experimental house site. Looking at the data for January in Table 3.4, the 1 day period that had the minimum amount of solar radiation for that month over the ten year period had only 52.9% of the radiation expected on an average day in January. The average daily radiation, from Table 3.1, is 1.19 kWh/ m2 for that day, so the value for the minimum 1 day period is 0.63 kWh/ m2, or 0.56 kWh/ m2 less than expected for that day. This shortfall is shown in Table 3.5. This amount of energy must now be supplied by the battery. Since the shortfall is 47.1% of the normal radiation the battery must supply the equivalent of 47.1% of one day, or 0.47 NO-SUN days. This number is shown in Table 3.6.

Table 3.4 Battery Sizing Parameters: Min. Available Insolation (taken from [3])

Minimum Available Insolation Over A Consecutive-day Period (%)												
Lat 51 Lon 106	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Min/1 day	52.9	58.2	45.8	38.1	14.1	16.9	5.25	19.8	22.2	23.6	45.3	41.4
Min/3 day	64.1	66.5	66.5	49.0	41.8	40.9	24.6	45.4	32.1	38.3	63.0	64.5
Min/7 day	74.1	71.4	69.8	71.9	67.2	61.2	61.4	53.1	60.3	61.8	65.2	82.9
Min/14 day	79.1	79.7	72.2	86.4	80.4	79.9	69.5	68.5	79.9	71.3	69.9	90.1
Min/21 day	84.6	89.3	81.7	89.8	87.6	85.4	81.9	83.8	82.3	79.8	73.8	90.5
Min/Month	94.1	97.2	93.6	96.2	89.7	90.5	88.2	89.7	86.1	84.0	83.4	95.7

The number of NO-SUN days shows the "worst case scenario" for which battery storage is needed. In Table 3.6, the largest number of consecutive NO-SUN days occurs for the 21 day period, where the battery must supply the deficit between the expected radiation and the radiation actually received. This is the equivalent of 3.21 days of radiation, or a total of 3.21 days at 1.19 kWh/ m^2, which is 3.82 kWh/ m^2. These parameters, combined with information on the load requirements, assist in the design of systems with a low failure rate.

Table 3.5 Battery Sizing Parameters: Solar Radiation Deficits (taken from [3])

Solar Radiation Deficits Below Expected Values Incident On A Horizontal Surface Over A Consecutive-day Period (kWh/m^2)												
Lat 51 Lon 106	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1 day	0.56	0.91	1.95	2.94	4.84	4.66	4.69	3.43	2.59	1.68	0.76	0.55
3 day	1.28	2.19	3.61	7.26	9.85	9.93	11.1	7.01	6.78	4.07	1.54	0.99
7 day	2.15	4.34	7.59	9.31	12.9	15.2	13.3	14.0	9.23	5.88	3.38	1.12
14 day	3.48	6.18	13.9	9.00	15.5	15.7	21.1	18.8	9.33	8.82	5.84	1.29
21 day	3.83	4.86	13.8	10.1	14.6	17.1	18.7	14.5	12.3	9.33	7.62	1.87
Month	2.17	1.68	7.13	5.39	17.9	15.9	17.9	13.6	13.8	10.8	6.90	1.24

Table 3.6 Battery Sizing Parameters: Equivalent NO-SUN Days (taken from [3])

Equivalent Number Of NO-SUN Or BLACK Days (days)												
Lat 51 Lon 106	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1 day	0.47	0.41	0.54	0.61	0.85	0.83	0.94	0.80	0.77	0.76	0.54	0.58
3 day	1.07	1.00	1.00	1.52	1.74	1.77	2.26	1.63	2.03	1.85	1.10	1.06
7 day	1.80	1.99	2.10	1.96	2.29	2.70	2.69	3.28	2.77	2.67	2.43	1.19
14 day	2.92	2.83	3.88	1.89	2.74	2.80	4.26	4.39	2.80	4.00	4.20	1.38
21 day	3.21	2.22	3.83	2.12	2.59	3.06	3.78	3.39	3.70	4.24	5.48	1.98
Month	1.82	0.77	1.98	1.13	3.18	2.83	3.63	3.18	4.14	4.93	4.96	1.31

Similar data for wind resources is not available, but a wind generator would be able to supply some of this deficit at some times.

3.2.3 Climate Data for Assessing Wind Resources

The viability of using a wind generator for a stand-alone power system depends on the average wind speed and the wind speed distribution. Based on data from the Saskatoon Airport at a 10 meter height, the average wind speed for the Saskatoon area is 16.7 km/h, which is distributed fairly evenly throughout the year. Wind data from the NASA SSE website provides airport data at 10 meter elevation, and also estimates wind data for various heights and terrain conditions.

The experimental house site has rolling prairie terrain with areas of bush and trees. Parameters for the wind data were set for this type of terrain, and at a height of 12 meters, which corresponds to approximately 40 feet, and which is the intended height for the proposed wind tower. Table 3.7 shows a comparison of the data from the Saskatoon Airport, the NASA SSE data at a height of 10 meters over airport type terrain and at a height of 12 meters over rural terrain with bushes, crops and groundcover). It is clear that the data from these two sources are not in agreement, but it is also evident that the rural agricultural terrain reduces the expected wind speed to about 84% of the wind speed for airport terrain. The SSE Methodology states that local data should be used where possible because the one degree resolution of the grid square is not an accurate way of determining wind speeds for a particular area. For this reason, the Saskatoon airport data was used as the basis for assessing the wind resources for the house site, with expected output adjusted for a wind speed that is 84% of the airport values.

Table 3.7 Average Monthly Wind Speed for Different Terrains (taken from [3])

Month	**SSE at 10 m Airport terrain (m/s)**	**SSE at 12m Rural terrain (m/s)**	**Saskatoon Airport (m/s)**	**Rural - 84% of Saskatoon Airport (m/s)**
January	3.67	3.09	4.43	3.72
February	3.50	2.95	4.43	2.94
March	3.47	2.92	4.74	2.91
April	3.75	3.16	5.01	3.15
May	3.51	2.95	5.01	2.95
June	3.25	2.74	4.74	2.73
July	3.01	2.53	4.43	2.53
August	3.02	2.55	4.43	2.54
September	3.25	2.74	4.74	2.73
October	3.44	2.90	4.74	2.89
November	3.64	3.07	4.43	3.06
December	3.68	3.10	4.43	3.09
Annual Average	**3.43**	**2.89**	**4.63**	**2.94**

The data from Table 3.7 provides a basis for comparison of different wind generator products from various manufacturers. This information was used to choose the model most appropriate and cost effective for the site.

4 DESIGN CALCULATIONS AND EXPECTED VALUES

The experimental house design minimizes heat and power requirements for a typical home built to national building code standards and operating a normal complement of household loads. Passive solar design techniques, within the limitations of the RTM design, are used to provide a substantial portion of the home's heating requirements. Optimizing the solar power system design involved many energy efficiency measures to reduce the power draw of the house loads, yet maintaining a comfortable life style.

4.1 Power System Design and Expectations

The power system design started with a basic cost analysis and a look at standard solar power system design practices to determine if 220V loads were feasible within the cost constraints. The initial estimate showed it would be better to design a 110V system, with propane for water heating, cooking and backup space heating. Operating 220 V loads requires a second inverter and also a larger charging system to provide the increased power usage from 220 V loads such as an electric stove. It was estimated that this would add approximately $15,000 to the cost of the renewable power system.

4.1.1 Load Analysis

Designing a solar power system that is cost effective for the homeowner means that the homeowner will have to make some choices about the household loads that are most important to him or her. While a solar power system is certainly capable of operating any size of load, cost considerations require a compromise and a consciousness of energy usage on a day-to-day basis. For a homeowner, this means making a choice of household loads that will supply the essentials such as water and mechanical systems and then selecting the appliances and devices that are believed to be most important to a fulfilling lifestyle. A load analysis determines the amount of energy in kWh used by the chosen selection of household loads so that the appropriate size of solar and / or wind charging system can be designed for the climate conditions of the area.

The experimental house was designed to operate the necessary mechanical systems for the house, such as a jet pump to pump water from a sandpoint well and a submersible septic pump, and also to operate the appliances and office and entertainment devices.

A load analysis table, as shown in Table 4.1, lists all the electrical loads of the house, with the rated power requirements of each device and the number of hours per day that they are expected to operate. The energy required to operate that load for a day can then be calculated (in Wh) as:

$$E_d(Wh) = \sum_{i=1}^{n} I_i V_i H_i \qquad (4.1)$$

where I_i and V_i are the current and voltage respectively of the i^{th} loads and H_i is the daily duty cycle of the i^{th} load in hours/day[26]. Values are listed in the more common units of kWh/day in Table 4.1.

There are some power losses through the inverter, so the total household loads must be adjusted for the efficiency of the inverter.

Table 4.1 Load Analysis for the Experimental House

Load	Rated Power (W)	Average Hrs/day	kWh/day
Mechanical:			
Water pump	1200	0.3	0.36
Septic pump	800	0.05	0.04
Kitchen Appliances:			
Fridge	404 kWh/yr	As rated	1.10
Coffee Maker	900	0.25	0.23
Toaster	900	0.2	0.18
Toaster Oven	1300	0.1	0.13
Electric Frying pan	1200	0.02	0.024
Slow Cooker	110	.1	0.011
Lighting and fans:			
10 lights @ 15 Watts	150	2	0.3
Ceiling fans (2 @ 12W ea.)	24	4	0.1
Office and Entertainment:			
Television (27”)	100	2	0.1
VCR	30	0.5	0.015
DVD Player	30	1	0.03
Radio	2	15	0.03
Stereo	20	2	0.04
Aquarium lights	45	3	0.14
Aquarium filters	20	24	0.48
Laptop Computer	50	6	0.3
Printer	10	1	0.01
Modem and wireless router	40	4	0.16
Laundry:			
Washer (front loading)	227 kWh/yr	0.5 of rated	0.3 [1]
Dryer (110 V) – seldom used	398 kWh/yr	0.1 of rated	0.1 [2]
Iron	1100	.05	0.05
Small Power Tools	600	.1	.06
Car Block Heater	1200	.01	.01
Battery chargers (cell phones, etc.)	6	2	.01
Total AC Load:			4.31
@ 90 % inverter efficiency:			4.74

[1] The energy rating in kWh/year is based on 416 “Normal Cycle” operations per year and includes the energy required to heat the water[29]. This is more than one load per day, which is not necessary for two people. The usage estimate has been adjusted accordingly, to 0.5 times the energy rating.

[2] This energy rating in kWh/year is also based on 416 operations per year[29]. Our usage would be less based on fewer loads through the washer and we often hang the clothes to dry. Again, usage has been adjusted accordingly.

Modern inverters have efficiencies of 90 to 95 per cent. Figure 4.1 shows efficiency curves for the Xantrex series of sine wave inverters which are commonly used for residential applications like this one.

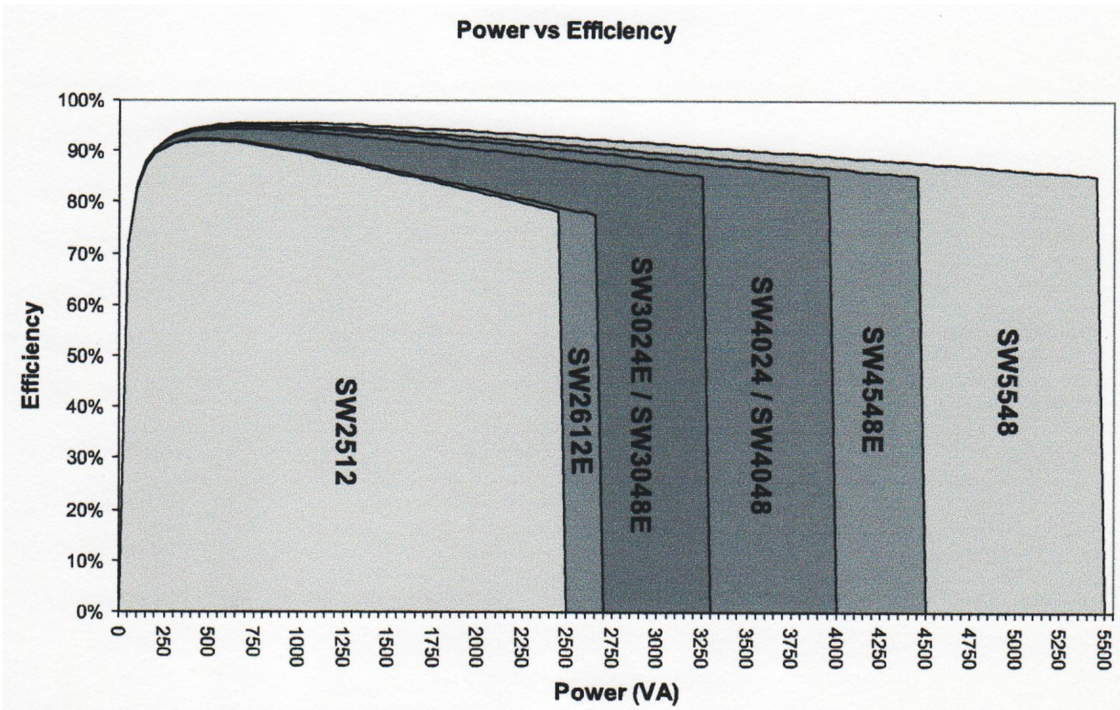


Figure 4.1 Power vs Efficiency Curve for Xantrex Sine Wave Inverters (taken from [9])

Using the lowest rated efficiency of 90%, the anticipated average daily load for the experimental house would be about 4.8 kWh.

Since the solar power system includes a monitor that shows charging or discharging current and the state of charge of the battery bank, the homeowner can adjust the daily load to suit conditions. If there is little sun or wind, large loads like the washer and dryer and electric cooking appliances can be avoided. Laundry and home renovations can be scheduled for days with excess power to avoid wasting this power through the dump load.

4.1.1.1 Water and Septic System

The system is designed to use standard 110 V pumps, readily available at local retail outlets, for the standard jet pump, convertible to deep or shallow well, and the submersible septic pump to a field. A large pressure tank, with a 13 gallon draw down is specified for the water system to reduce the frequency of power up conditions that produce a short duration spike in power demands.

4.1.1.2 Domestic Hot Water

The domestic hot water system was chosen to be an instantaneous 117,000 BTU/hr Bosch Aquastar water heater, fuelled by propane, to eliminate the need for 220V electric water heaters and the need to constantly heat a hot water tank. Hot water is available with little delay, no more than with a standard hot water heater. The initial cost is higher than for a standard gas water tank, but this saves energy costs in the long term.

4.1.1.3 Appliances and Fans

For the 1992 Advanced Houses Program, discussed in Chapter 2, the appliance and fan energy target was set at 3,838 kWh per year, which was a 50% reduction in the energy consumed by R-2000 homes[2]. The target for this experimental house is 1400 kWh per year, less than half of the target for the Advanced Houses program. This seems like a very ambitious target but is made manageable by factor of 2 improvements in energy efficiency of major appliances, as shown in Chapter 2.

The load analysis includes a number of small appliances with resistive heaters that consume a large amount of power but are used only intermittently so the overall contribution to the daily load is not significant. These types of loads include the toaster, toaster oven, electric frying pan, slow cooker, microwave and coffee maker. An electric toaster typically uses about 900 watts but is only used for a few minutes a day, making its contribution to the daily load only about one tenth of kilowatt hour. Similarly, microwaves and toaster ovens use about 1300 watts when operating but contribute very little to the daily load. Appliances like a coffee maker and a slow cooker operate on thermostats so that although they are on for longer periods the heating elements are only on intermittently during this time.

Other small appliances such as cake mixers, food processors and small power tools only require the use of small electric motors and are not used on a daily basis so their contribution to the daily load requirements are too small to be significant.

This house was designed with two ceiling fans to circulate warm air throughout the house. Ventilation requirements, including heat recovery ventilators and associated fans, are required according to the National Building Code in many areas and this requirement will add an extra load to future projects.

4.1.1.4 Lighting

Most of the interior and exterior lighting is designed to be compact fluorescent bulbs, with one outside light on a timer. One quartz halogen light is included in the design to view a small gallery of holograms, but is seldom used. The compact fluorescent lights range from 13 to 26 watts, and include one trilight and a 26 W light at the top of the stairwell.

4.1.2 Solar Array

In northern latitudes there is a large difference between the length of the potential charging day on the summer solstice and the winter solstice. Designing a solar power system for such conditions usually involves a compromise that aims to meet the load requirements for three quarters of the year and uses generator backup to supplement the solar and wind charging for the one quarter of the year with the shortest days. This is a compromise designed to make the system more cost efficient, since designing a power system to meet winter needs would result in excess energy in the summer that would often be wasted.

The load requirements and the average expected insolation at the proposed site are used to calculate the appropriate size of the solar array. Solar radiation data were used from the NASA SSE data set for the grid square from 51 to 52 degrees latitude and 106 to 107 degrees longitude. The proposed building site is situated near the northwest corner of this grid square.

A solar cell receives the maximum amount of power if it is tilted at an angle perpendicular to the sun's rays. To achieve this condition for all times of the day and days of the year would require a two-axis tracking device which would add considerable expense and complexity to the system. Most residential systems have the array at a fixed angle or at two tilt angles that are adjusted for the season. This method produces a reasonable compromise to maximize the solar gain and help shed snow in the winter. With the steeper angle and the dark smooth surface of the solar panels, snow and frost melts quickly in full sunlight. When there is little sunlight available, snow can be brushed off the panels to improve solar collection, but under these conditions the difference is not significant.

Table 4.2 shows the size of solar array required for a two tilt angle system.

Table 4.2 Array Size to Meet a 4.8 kWh/day Load Requirement with two tilt angles, at Average Solar Radiation and Minimum Solar Radiation

Month	Daily Avg. Radiation at tilt 51º ($kWh/m^2/day$)	Daily Avg. Radiation at tilt 66º ($kWh/m^2/day$)	Required Array Size for Avg. Rad. (kW)	Daily Min. Radiation at tilt 51º ($kWh/m^2/day$)	Daily Min. Radiation at tilt 66º ($kWh/m^2/day$)	Required Array Size for Min. Rad. (kW)
January	2.92	**3.1**	2.06	2.66	**2.82**	2.26
February	4.22	**4.33**	1.47	4.05	**4.15**	1.54
March	**5.11**	4.97	1.25	**4.68**	4.54	1.41
April	**5.19**	4.74	1.23	**4.96**	4.53	1.41
May	**5.23**	4.56	1.22	**4.67**	4.08	1.56
June	**4.84**	4.2	1.32	**4.37**	3.82	1.67
July	**4.38**	3.85	1.46	**3.86**	3.41	1.87
August	**4.26**	3.81	1.50	**3.77**	3.38	1.89
September	**3.99**	3.77	1.60	**3.31**	3.11	2.05
October	3.5	**3.5**	1.82	2.73	**2.71**	2.36
November	3.02	**3.16**	2.02	2.29	**2.38**	2.68
December	2.58	**2.76**	2.31	2.41	**2.57**	2.48
Annual	4.1	3.89	1.56	3.64	3.45	1.85

Since the power system design includes both a solar panel array and a wind generator, the solar array only needs to supply about one third to one half of the load requirements.

The system was designed with a 920 Watt solar array consisting of eight 115 Watt Evergreen solar panels. This product was selected because their innovative string ribbon manufacturing process provided a comparable efficiency rating at a lower cost than other manufacturers. In traditional solar cell manufacturing technology, a silicon crystal is produced and then cut into very thin wafers which form the individual solar cells. This means that the material cut by the saw blade is wasted and breakage is also a problem because the wafers are so thin. Evergreen technology uses a vat of molten silicon and draws two strings through the melt, producing a thin film with crystalline properties that reduces wastage from saw cuts and breakage [27]. A diagram of this method is shown in Figure 4.2.

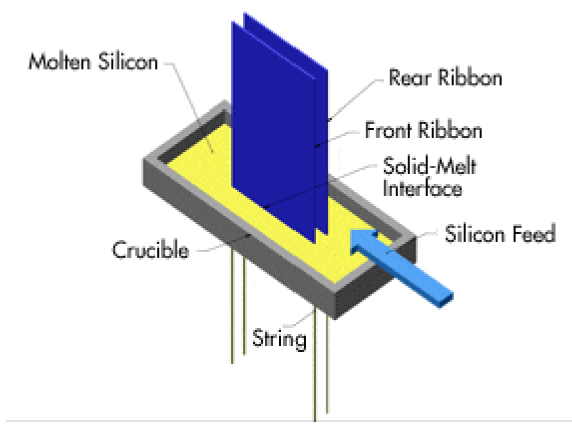


Figure 4.2 Evergreen's String Ribbon Production Process (taken from [27])

4.1.3 Expected Solar Power Output

Two approaches were taken to determine the expected power output of the solar array. The array was designed to be adjustable for two angles, 51º and 66º. The 51º angle corresponds to the latitude of the house site and would provide the maximum output for a fixed angle array. The 66º angle is halfway between the optimum angles for the equinox and the winter solstice so provides the maximum output over the winter months with only the one angle adjustment.

One could simply use the average radiation values from the NASA SSE data set to determine the expected output, as shown in Table 4.3, but the more local solar radiation data from the SRC station showed lower solar radiation values for the winter months than the minimum radiation values from the SSE data set, so a projected output was also made based on the SSE data set minimum values. This is shown in Table 4.4. The minimum values show the minimum solar radiation of any day in that month, over the 10-year data collection period. In both tables, the bolded angles correspond to the optimum angles for those months. The expected monthly output is calculated as 75% of the Daily Radiation multiplied by the power rating of the array. The 75% multiplier is used to compensate for the efficiency of the charge controller (83%) and the batteries (90%).

Table 4.3 Expected Monthly Output of a 0.92 kW Solar Array with Two Tilt Angles with the Average Solar Radiation over a 10-year Period

Month	Daily Avg. Radiation at tilt 51º ($kWh/m^2/day$)	Daily Avg. Radiation at tilt 66º ($kWh/m^2/day$)	Expected Monthly Solar Output at Opt. Angle (kWh)
January	2.92	**3.1**	66.3
February	4.22	**4.33**	83.7
March	**5.11**	4.97	109.3
April	**5.19**	4.74	107.4
May	**5.23**	4.56	111.9
June	**4.84**	4.2	100.2
July	**4.38**	3.85	93.7
August	**4.26**	3.81	91.1
September	**3.99**	3.77	82.6
October	3.5	**3.5**	74.9
November	3.02	**3.16**	65.4
December	2.58	**2.76**	59.0

Table 4.4 Expected Monthly Output of a 0.92 kW Solar Array with Two Tilt Angles with the Minimum Solar Radiation over a 10-year Period

Month	**Daily Min. Radiation at tilt 51º ($kWh/m^2/day$)**	**Daily Min. Radiation at tilt 66º ($kWh/m^2/day$)**	**Expected Monthly Solar Output at Opt. Angle (kWh)**
January	2.66	**2.82**	60.3
February	4.05	**4.15**	80.9
March	**4.68**	4.54	100.1
April	**4.96**	4.53	102.7
May	**4.67**	4.08	99.9
June	**4.37**	3.82	90.5
July	**3.86**	3.41	82.6
August	**3.77**	3.38	80.6
September	**3.31**	3.11	68.5
October	2.73	**2.71**	58.0
November	2.29	**2.38**	49.3
December	2.41	**2.57**	55.0

4.1.4 Wind Power System

The average monthly load requirements for the experimental house and the expected output from the solar array are shown in Table 4.5. The average load requirements are calculated as the daily load requirement of 4.8 kWh multiplied by the number of days of the month. A wind generator was included in the design of the power system to supplement the solar power output, especially during the winter season.

Table 4.5 Expected Monthly Output of a 0.92 kW Solar Array with Two Tilt Angles with the Minimum Solar Radiation over a 10-year Period

Month	Expected Monthly Solar Output at Opt. Angle (kWh/month)	Average Load Requirements (kWh/month)
January	60	149
February	80	134
March	100	149
April	103	144
May	100	149
June	90	144
July	83	149
August	81	149
September	69	144
October	58	149
November	49	144
December	55	149

A wind generator's output varies exponentially with the wind speed and, at any given wind speed, depends primarily on the swept area of the propeller blades.

The energy of the wind varies with the cube of the wind speed, so if the wind speed is doubled the power output increases by a factor of 8. This is illustrated in Figure 4.3 which shows that a wind speed of 8 m/s produces an output of 314 W/m^2 while double the wind speed produces 2509 W/m^2 [32]. Since the average wind speed for any given period is made up of many intervals of varying wind speeds, the average is not a good indicator of the actual power output over any given period. For example, if the average wind speed consists primarily of winds close to the average, the power output would be very different from a situation where the average consists of extended periods with very low wind speeds and some at very high wind speeds.

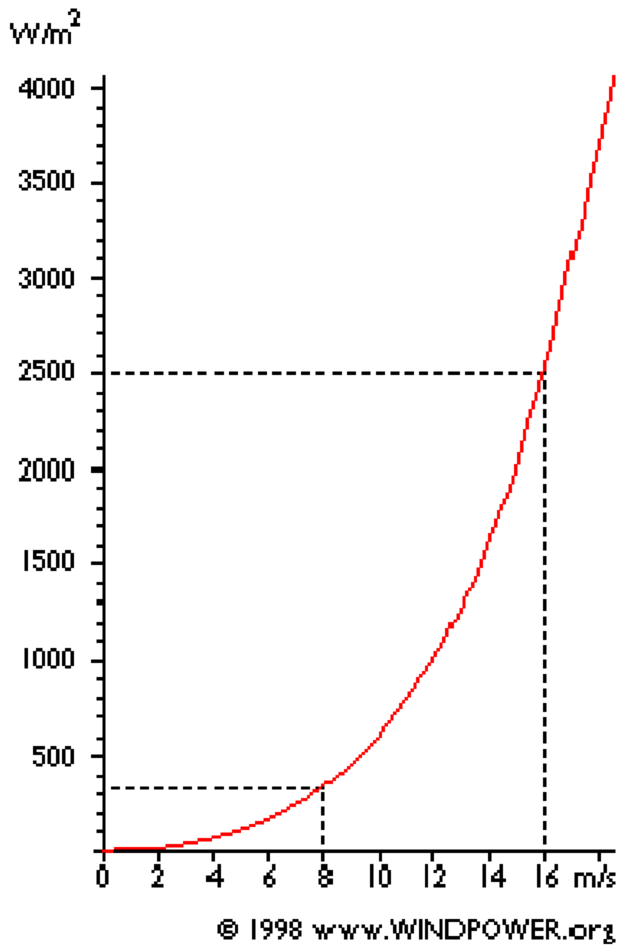


Figure 4.3 Energy of the Wind (taken from [32])

For this reason the wind speed distribution is just as important for determining wind generator output as the average wind speed. The most common wind distribution approximates a Rayleigh distribution curve with a shape factor (k) equal to 2 [32]. A typical wind distribution curve with this shape factor is shown in Figure 4.4. The vertical line at about 6.8 m/s indicates the mean power of the wind. Many wind turbine manufacturers base their output charts on the Rayleigh distribution [32].

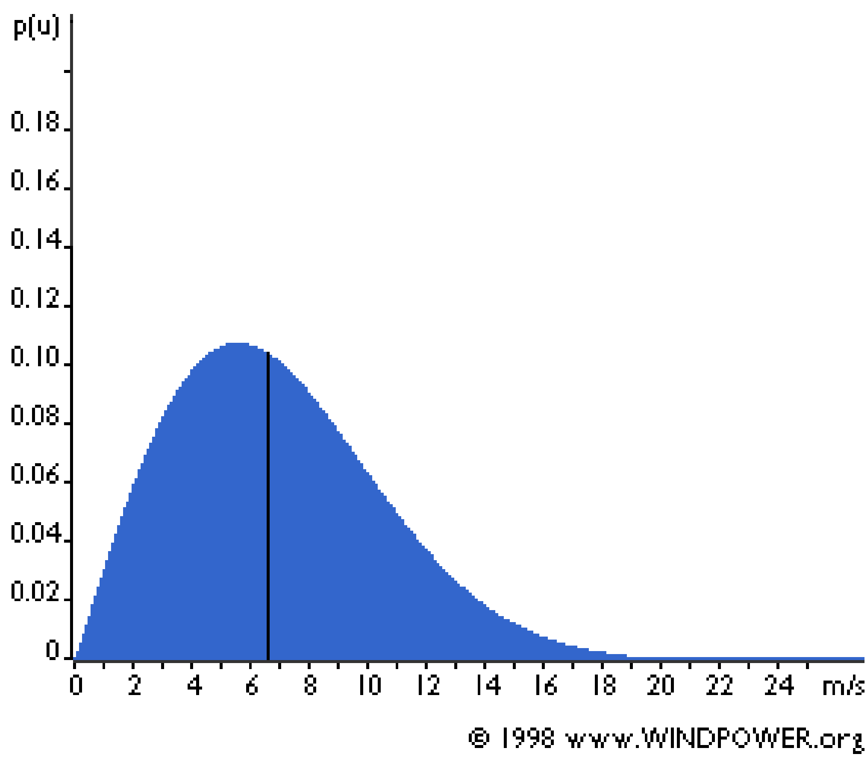


Figure 4.4 A typical Rayleigh Distribution (shape factor 2) [32]

The other main factor that determines a wind generator's power output is the swept area of the blades. The output power is directly proportional to area swept out by the generator's propellers. These two factors are evident in Equation 2.1 in Chapter 2, which describes the power of the wind passing through a circular area.

Manufacturers generally publish power curves to show the power output of their products at various wind speeds. Wind generators from several different manufacturers were compared on the basis of price and of the power output at the average wind speeds for the proposed building site [28]. A comparison of the four wind generators that had the necessary output within the budget constraints is shown in Appendix A. The Whisper H80 (now the Whisper 200) was found to be the lowest cost per watt. It is rated to produce 125 kWh / month at a wind speed of 10 mph (4.5 m/s) and 193 kWh/month at 12 mph (5.4 m/s). The average wind speed during November, December and October is 9.9 mph, so this would be more than adequate to supplement the expected 50 kWh / month from the solar array during this period.

A power curve for the Southwest Windpower Whisper 200 (formerly the Whisper H80) and Whisper 100 wind generators is shown in Figure 4.5 and the expected monthly energy output versus average wind speed is shown in Figure 4.6. Information from the power curve cannot be directly used to calculate the expected monthly energy output because the wind distribution is a crucial element in this calculation. The Southwest Windpower energy output chart is based on a Rayleigh distribution with a shape factor of 2, which is the most common shape factor for wind distributions.

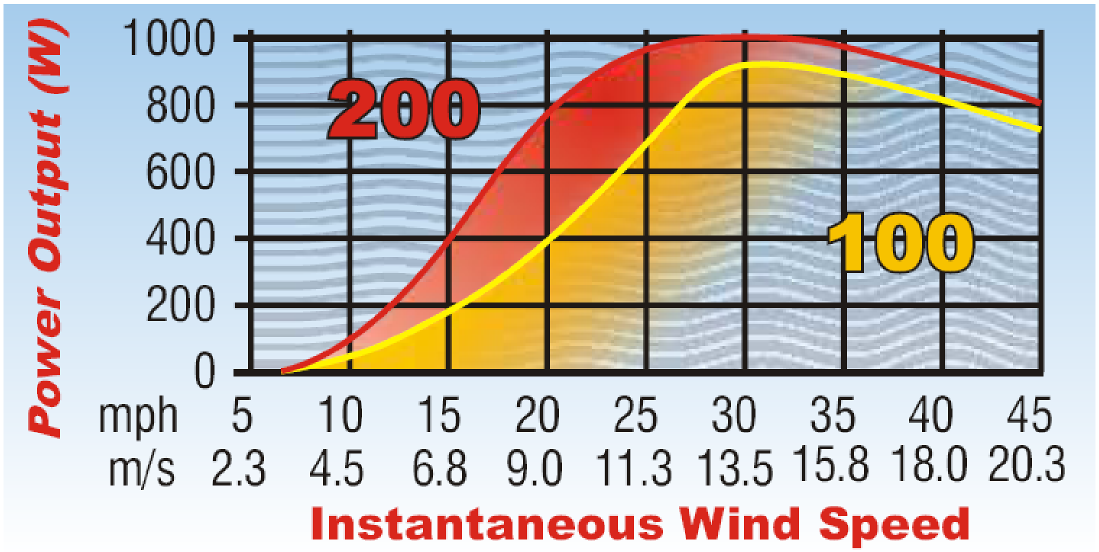


Figure 4.5 Power Curves for the Whisper 200 (formerly H80) and Whisper 100 (formerly H40) Wind Generators (taken from [34])

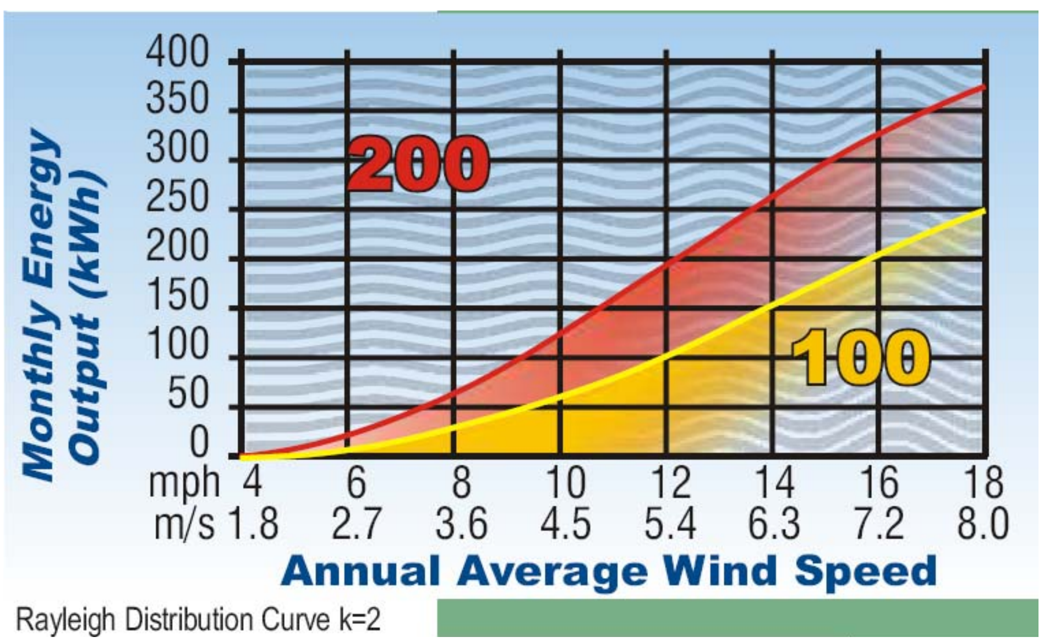


Figure 4.6 Monthly Energy Output of the Whisper 200 (formerly H80) and Whisper 100 (formerly H40) Wind Generators (taken from [34])

The Whisper 200 has the following specifications:

- Swept Area: 7.4 square meters
- Rated Power: 860 Watts at the rated wind speed of 10.5 m/s
- Peak Power: 950 Watts at a wind speed of 11.4 m/s
- Peak Amps: 33 A @ 29 V
- Cut-in Wind Speed: 3.3 m/s
- Rated electricity at 5.7 m/s average wind speed: 193 kWh/month

The terrain at the building site is rolling prairie with some sections of bush so, as discussed in Section 3.2.3, the power output was expected to be about 16 % less than at the airport with its flat terrain.   The wind generator was designed to be mounted on a 12 meter high tower to bring it above the turbulent layer that generally extends to about 9 meters.

4.1.5 Expected Wind Power Output

Power output from the Whisper 200 wind generator was projected using the manufacturer's monthly energy output specifications and the wind data (climate normals) from the Saskatoon Airport weather station. The output was estimated using wind speeds of 84% of the Saskatoon Airport data, to adjust for terrain similar to the proposed building site. The expected power output is shown in Table 4.6.

Table 4.6 Expected Monthly Output of the Southwest Windpower 200 Wind Generator

Month	Saskatoon Airport (m/s)	Expected Output at Airport (kWh)	Expected Output at House Site (84% of Airport) (kWh)
January	4.43	128	108
February	4.43	128	108
March	4.74	150	126
April	5.01	165	139
May	5.01	165	139
June	4.74	150	126
July	4.43	128	108
August	4.43	128	108
September	4.74	150	126
October	4.74	150	126
November	4.43	128	108
December	4.43	128	108
Annual Average	**4.63**	**142**	**119**

4.1.6 Expected Total Power Output of the Charging System

Table 4.7 shows the combined solar and wind energy that can be expected using the minimum solar radiation data values from the SSE data set and the wind data from the SSE data set, adjusted for the building site terrain. This provides minimum values for the expected performance, so it is anticipated that the actual performance will be somewhat better.

Table 4.7 Expected Total Monthly Output of the Solar Array and the Wind Generator

Month	Expected Minimum Solar Output (kWh)	Expected Wind Output (kWh)	Expected Total Output (kWh)	Average Load Requirements (kWh/month)
January	60	108	168	149
February	80	108	188	134
March	100	126	226	149
April	102	139	241	144
May	100	139	239	149
June	90	126	216	144
July	83	108	191	149
August	81	108	189	149
September	69	126	195	144
October	58	126	184	149
November	49	108	157	144
December	55	108	163	149

One can see from Table 4.7 that the average load requirement would be met throughout the year, assuming that the adjustment factor of 84% is appropriate for the terrain at the house site. This was not known when the house was designed, but was tested during the performance evaluation by installing an anemometer at the site for a five month period in 2006. Actual yearly values can vary widely from these averages, so the backup generator will provide charging power for any shortfall.

4.1.7 Battery Bank and System Voltage

Most residential renewable power systems use a 24 volt battery bank and charging system because efficiencies are better than for the customary 12 volt systems, and because larger inverters are available at this system voltage. Other options include 36 volt and 48 volt system. The 24 volt system was chosen because it is the most common and therefore has the most complete selection of compatible components and accessories.

Since large capacity deep cycle batteries are generally available in 2 volt cells, this system will require a bank of twelve cells.

In Chapter 3 battery sizing requirements were discussed. Table 3.6 shows the equivalent number of no-sun days for consecutive periods of 1, 3, 7, 14 and 21 days and for the month. The longest consecutive period of no-sun days is 5.48 days for the 21-day period in November, but this is the only period over 5 no-sun days. For most months and time periods three days of autonomy would be sufficient for a solar charging system. Since this is designed as a PV/wind/generator hybrid system, an autonomy of 3 days is considered to be adequate. Table 4.3 shows a comparison of available batteries with costs and days of autonomy for the system load.

Table 4.8 Battery Days of Autonomy for a load of 4.8 kWh/day (200 AH/day) and various battery capacities

No. of Batteries	Capacity (AH) (100 hr rate)	De-rated Capacity (AH)	Days of Autonomy	Retail Cost	Battery Type
12	2023	850	4.2	$6,312	KS-27
12	1904	800	4.0	$5,952	KS-25
12	1712	719	3.6	$5,412	KS-23
12	1556	654	3.3	$4,932	KS-21
12	1401	588	2.9	$4,428	KS-19
12	1245	523	2.6	$4,020	KS-17
12	1090	458	2.3	$3,612	KS-15

De-rated Capacity = Total Capacity multiplied by 84%, to account for the efficiency of the batteries and temperature effects, and 50%, which is the maximum depth of discharge recommended by the manufacturer.
Runtime = De-rated Capacity / (AH/day)

4.1.8 Charge Controller

A renewable energy system must include a charge controller that is rated for about 1.25 times the charging current that is specified by the manufacturers of the solar panel array and the wind generator. Specifications are based on test conditions at a particular altitude and temperature so actual current delivered by the units can be higher depending on the local climate conditions and the amount of diffuse radiation. Therefore the charge controller must be able to handle more than the maximum expected charging current.

The Whisper 200 wind generator includes a charge controller for the wind generator and a PV array. It is designed with a resistive dump load and a metering section that provides information on the charging, battery and dc load currents. Although more sophisticated Maximum Power Point Tracking (MPPT) controllers are available for the solar array, it was decided to use only the controller supplied with the wind generator for this experiment.

4.1.9 Inverter

For residential applications that include a variety of loads, a sine wave inverter is the best choice because it delivers power more efficiently and reduces harmonics and noise that may cause problems with some loads. The power rating of the inverter should be sufficient to operate any loads that would run simultaneously. The load analysis in Table 4.1 shows a number of loads, such as the water pump, septic pump and the fridge, where the homeowner does not really have any control over when they start up. If all of these loads are running simultaneously this would add up to about 2900 Watts. This is a situation that would not occur very often because the water pump usually runs only once or twice a day and the septic system only once every few days. A 4000 Watt inverter is a cost effective choice that would be able to operate many loads at the same time, as long as the homeowner did not try to operate five or six large loads (like the electric frying and the microwave) at the same time. The literature shows that many residential systems operate successfully with approximately 4000 Watt inverters.

The Xantrex SW4024 4000 watt sine wave inverter was selected for this design because it produces an acceptable quality sine wave and provides many features and programmable options at a very competitive price. Figure 4.7 shows the utility-grade sine wave output from this inverter.

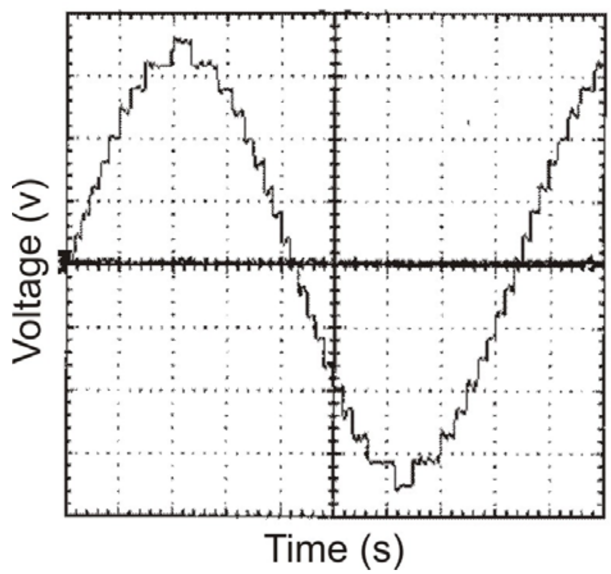


Figure 4.7 Sine Wave Output of the Xantrex SW4024 Inverter (taken from [9])

The output waveform is produced by mixing the output of three transformers, each driven by its own inverter, and results in a waveform with 34-52 steps per cycle. If load demands are heavy or the dc input voltage is low, the output waveform has a larger number of steps. The harmonic distortion for this output is typically 3-5% [9]. Inverters with pure sine wave outputs are available, but at higher cost, and are not needed for most household loads.

4.1.10 Complete Power System

The complete system design is shown in the pictoral diagram in Figure 4.8. The EZ-Wire System Center, included with the Whisper H80 wind generator, is shown in block form in the diagram. The “System Center” includes bonding blocks, wind generator brake, solar array disconnect, dump load and the rectifiers and power supply circuit to provide the 24 vdc output for battery charging. A shunt calibrated at 50 mV/500 amps provides a voltage input for the TM-500 meter that displays charging and discharging current and battery status.

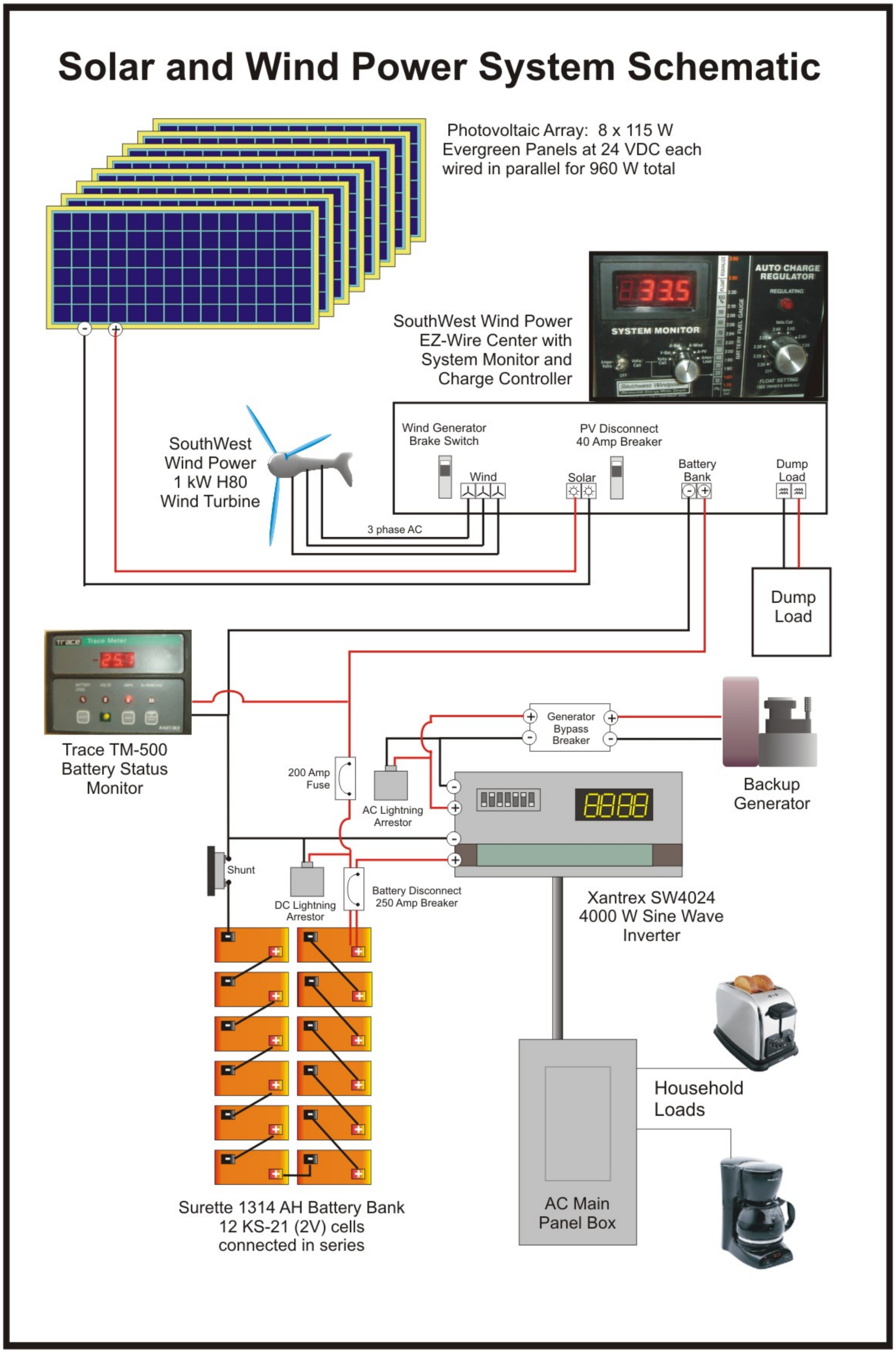


Figure 4.8 Schematic Diagram of the Stand Alone Solar and Wind Power System

4.1.11 Budget Considerations

Although many consumers place sustainability above the cost savings of using renewable energy, the cost must still be reasonable compared to standard fossil fuel sources to make the system affordable to average income families. Determining payback period and Return on Investment (ROI) by comparing the power usage of the experimental house to the same power usage for a grid tied system provides one measure of the cost effectiveness of the system. However, it is not really a true measure because living on a renewable power system with a limited amount of power available involves some lifestyle changes that people are unlikely to make if they were using a standard grid tied system. Using a renewable energy system fosters an awareness of energy usage that promotes energy conservation to a degree not realized with grid connections.

A family typically uses about $1200 a year in purchased electrical energy but the experimental house, if connected to the grid would use only about $450 of purchased energy per year. Assuming a usage of $450 a year provides a rather long payback period and a very low ROI. RETScreen Project Analysis software was used to perform a financial analysis for this system. System costs are shown in Table 4.9. The lifetime of the equipment is expected to be over twenty-five years for the solar panels, twenty to thirty years for the wind generator, fifteen to twenty years for the batteries, and over twenty years for the inverter and charge controller. Warranties are twenty-five years for the solar panels, ten years for the batteries, five years for the wind generator (which in this case includes the charge controller) and two years for the inverter.

Table 4.9 Costs for the Experimental House Renewable Power System

Initial Capital Costs

Description	Part Number	Retail Price	Number	Total
115 W Evergreen solar panels	EV-115	$989.00	8	$7,912.00
Xantrex 4000W Powerboard	PB-SW4024	$5,458.00	1	$5,458.00
Lightning Protection (AC+DC)	PB-LA-ADD	$177.00	1	$177.00
TM-500 meter add-on	PB-TM-500-ADD	$356.00	1	$356.00
Batteries - 1314 Ahr	KS-21	$444.00	12	$5,328.00
WATER MISER CAPS	Water Miser Caps	$6.00	12	$72.00
Whisper H80 Wind Generator	WP-H80	$3,644.00	1	$3,644.00
40 ft. guyed Tower, concrete pad	custom	$1,000.00	1	$1,000.00
Install wind generator and tower		$800.00	1	$800.00
Battery Box with vent	custom	$180.00	1	$180.00
Install solar power system		$1,000.00	1	$1,000.00
Solar panel mounts & wiring	custom	$500.00	1	$500.00
Gas Generator	Generac 4000	$1,300.00	1	$1,300.00
Subtotal				$27,727.00
PST (5%)				$1,222.35
GST (6%)				$1,663.62
Initial Costs Total				$30,612.97

Annual Costs

Operation and Maintenance:				
Gas Generator, Wind Generator	Maintenance			$30.00
Contingency		10%		$3.00
Fuel for gas generator				$160.00
Annual Costs Total				$193.00

Periodic Costs

Inverter Repair	15 years			$500.00
Battery Replacement	15 years			$4,000.00
Periodic Costs Total				$4,500.00

The results of the RETScreen financial analysis, using the input from Table 4.9 for the experimental house, are shown in Table 4.10. The project lifetime is considered to be 29 years, which includes some maintenance, repair and replacement costs. For simplicity, financing of the system is not included in this analysis but would need to be considered if financing is required for the system.

Table 4.10 RETScreen Financial Summary for the Experimental House with Grid Connection Cost of $10k

Financial Feasibility		
Pre-tax IRR and ROI	%	0.6%
After-tax IRR and ROI	%	0.6%
Simple Payback	yr	45.5
Year-to-positive cash flow	yr	27.8
Net Present Value - NPV	$	(5,243)
Annual Life Cycle Savings	$	(256)
Benefit-Cost (B-C) ratio	-	0.71

The Financial Feasibility indicators shown in this analysis are defined by RETScreen as [25]:

- Internal Rate of Return (IRR) or Return on Investment (ROI)

  This is the rate that causes the Net Present Value (NPV) to be zero and is the true interest yield provided by the project equity over its life. It is calculated by solving for IRR in equation 4.1

$$0 = \sum_{n=0}^{N} \frac{C_n}{(1+IRR)^n} \tag{4.1}$$

  where N is the project life in years, and C_n is the cash flow for year n. C_0 is the equity of the project and represents the cash flow for year zero.

- Simple Payback

  This is the number of years it takes for the cash flow (excluding debt payments) to equal the total investment.

- Net Present Value (NPV)

  This is the value of all future cash flows, discounted at the discount rate, in today's currency.

- Annual Life Cycle Savings (ALCS)

  This is the levelised nominal yearly savings having exactly the same life and NPV as the project, and is calculated as shown in Equation 4.2.

$$ALCS = \frac{NPV}{\frac{1}{r}\left(1 - \frac{1}{(1+r)^N}\right)} \tag{4.2}$$

- Benefit-Cost Ratio (B-C)

  This is an expression of the relative profitability of the project, and is calculated as the ratio of the present value of annual revenues (income and/or savings) less annual costs to the project equity.

If these indicators are calculated and compared to the more usual usage of an average family living in a grid connected home by adding $750 to the annual energy savings, the results show a better ROI and payback period. This case is shown in Table 4.11. Although not a true financial indicator, it takes into account that most people living in grid connected homes are not nearly as energy conscious because they are not living with the constant awareness of their energy usage.

Table 4.11 RETScreen Financial Summary for the Experimental House Compared to Typical Grid Usage

Financial Feasibility		
Pre-tax IRR and ROI	%	7.4%
After-tax IRR and ROI	%	7.4%
Simple Payback	yr	15.6
Year-to-positive cash flow	yr	12.3
Net Present Value - NPV	$	16,507
Annual Life Cycle Savings	$	807
Benefit-Cost (B-C) ratio	-	1.93

As the location of an off-grid home becomes more remote and the cost of grid connection increases, the payback period becomes shorter, as shown in Table 4.12 for a grid connection cost of $20,000 and, at a connection cost of $27,800, the payback period becomes zero. This is shown in Table 4.13.

Table 4.12 RETScreen Financial Summary for a Grid Connection Cost of $20k

Financial Feasibility		
Pre-tax IRR and ROI	%	4.8%
After-tax IRR and ROI	%	4.8%
Simple Payback	yr	21.7
Year-to-positive cash flow	yr	21.5
Net Present Value - NPV	$	1,692
Annual Life Cycle Savings	$	94
Benefit-Cost (B-C) ratio	-	1.22

Table 4.13 RETScreen Financial Summary for a Grid Connection Cost of $27,800 – Immediate Payback

Financial Feasibility		
Pre-tax IRR and ROI	%	positive
After-tax IRR and ROI	%	positive
Simple Payback	yr	(0.0)
Year-to-positive cash flow	yr	immediate
Net Present Value - NPV	$	9,492
Annual Life Cycle Savings	$	526
Benefit-Cost (B-C) ratio	-	(776.08)

The financial analysis indicates that, from strictly a payback or ROI point of view, an off-grid solar power system is not economically viable for the grid connection cost of $10,000 at the experimental house site. However, this analysis does not consider the intangible benefits of independence and self sufficiency, and greenhouse gas and pollution reduction.

4.2 House Design and Construction

The experimental house was built to national building code standards and designed to provide solar gain and efficient insulation at a price that is cost competitive with standard homes.

4.2.1 Passive Solar Design

The house design was meant to be an experiment so I wanted to keep the footprint as small as possible. However, it needed to be large enough for two people (my husband

and me) and also provide some office space and a spare bedroom for visiting adult children. We planned to live in the house for a few years while we assessed the performance of the passive solar design and the stand-alone power system.

I chose a one-and-a-half story format with open landing and vaulted ceilings in the single story section because this was more efficient for heating and also gave a feeling of space in what was actually a very small house. The main floor is 24 feet by 28 feet with a 12 foot by 28 foot second floor. The total developed floor area of the house is about 1000 square feet. Figure 4.9 shows the main floor layout of the house, and Figure 4.10 shows the layout of the upper story.

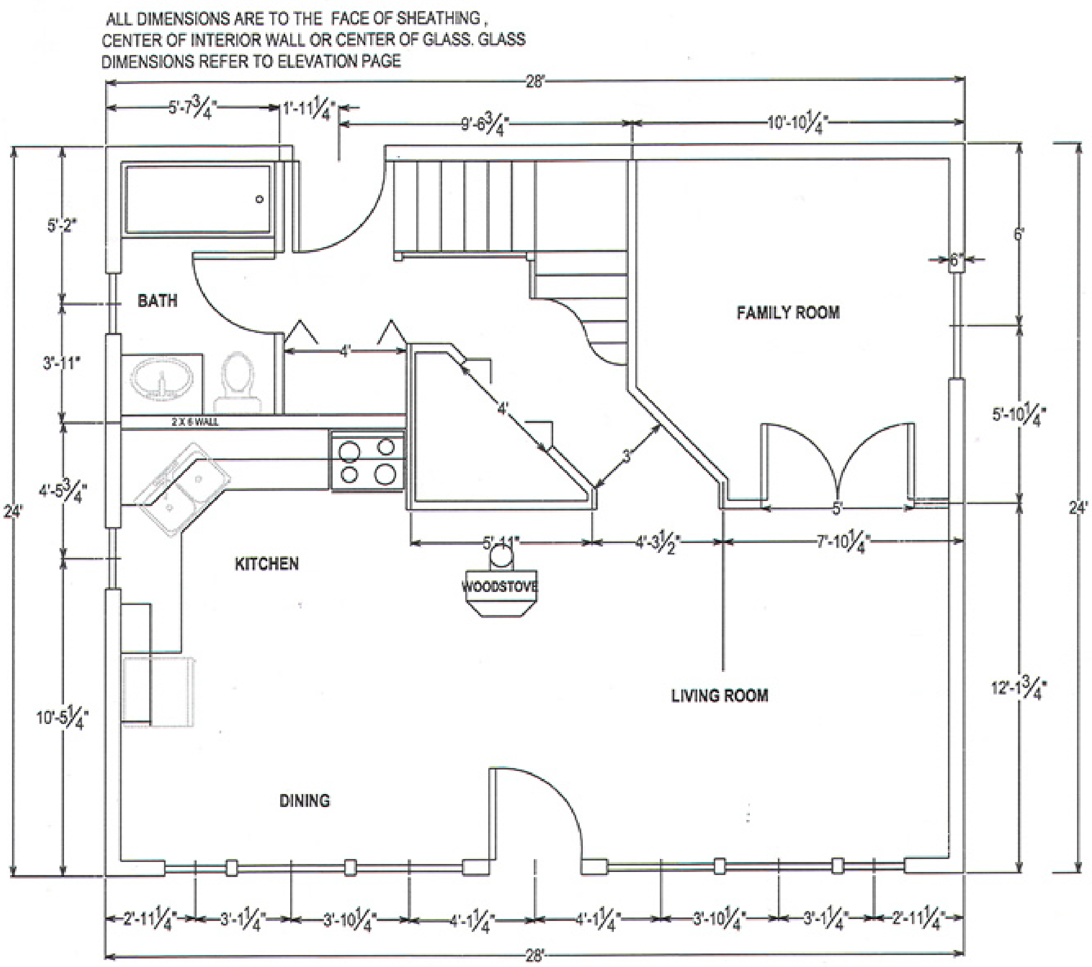


Figure 4.9 The Main Floor of the Experimental House

The power system is housed on the main floor, in the triangular shaped closet behind the woodstove. On the upper story, the laundry is in the small closet off the landing, and the on demand hot water heater is in the closet of the west bedroom, which is used as an office.

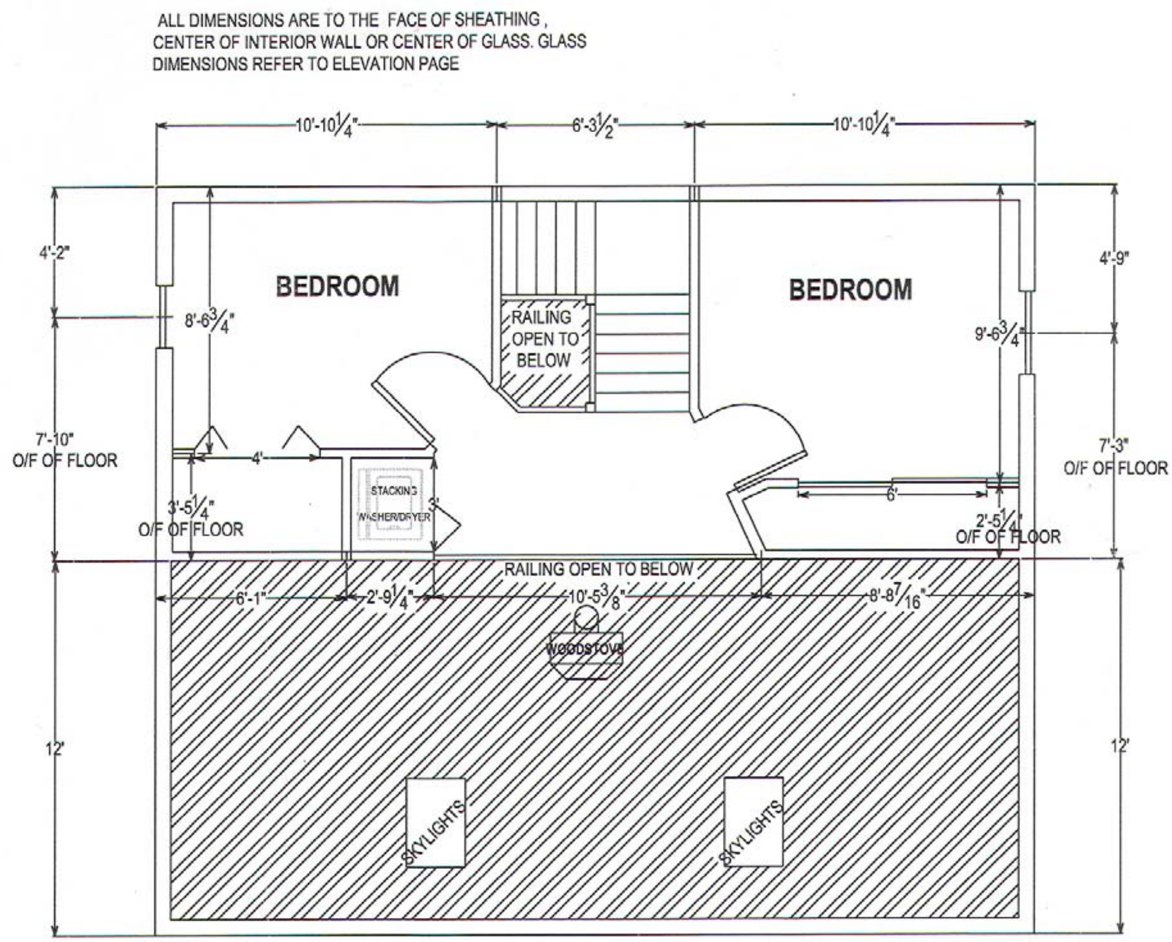


Figure 4.10 The Upper Story of the Experimental House

The 28 foot wall is oriented south. The glass area of the south facing windows is 9.3 % of the inside floor area of the house. Since this is more than 7 %, some thermal mass is recommended to balance the heat distribution over the course of the day and night 12]. The extra 2.3 % of glass area constitutes 20 square feet of extra glass which is partially balanced by approximately 140 square feet of 2” to 4” thick thermal mass in the floor or walls. Fifty square feet of thermal mass, in the form of 2.5” thick mortarless brick (Nova brick) facing, was installed on the wall behind the woodstove. A 25 square foot area of tile flooring was used as the base of the woodstove and the cast woodstove itself provides some further thermal mass. This is still somewhat short of the recommended area of thermal mass [12] but, since the house is an RTM design, weight also had to be considered, so the smaller area of thermal mass was used.

The north wall has almost no glass, except for a small semi-circular insert in the entry door. The east wall has 2 % glass and the west wall has 1.9 % glass. The percentage of glass on the east and west walls is partly dictated by the minimum size requirements for bedroom windows in the National Building Code. The south facing roof is at a 12/12 pitch and includes two skylights to admit light to the upper story and provide some extra ventilation. The skylights do not open but have a vent at the top that can be opened in any type of weather, because it is protected by a flashing on the outside. The north facing roof is at a 6/12 pitch, so the north wall of the bedrooms is five feet high, which adds character to these small bedrooms.

The south wall of windows is designed to give a full length clear view at the central door and the windows on either side, but the remaining windows are shorter so that furniture can be placed against the walls under the windows. This allows more flexibility in the arrangement of furniture, an important consideration in such a small house. Figure 4.11 shows the south and west views of the house.

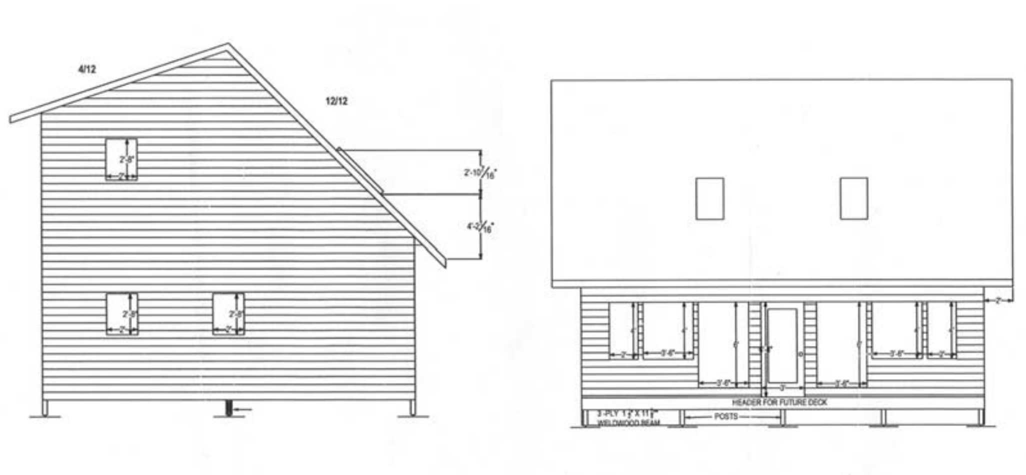


Figure 4.11 The west and south walls of the experimental house

4.2.2 Building Envelope and Space Heating

The building structure was designed as follows:

- Exterior walls use 2"x 6" studs, R20 fiberglass insulation, 6 mil sealed vapour barrier, plywood sheathing and drywall. An engineered floor and truss system with LVL beams and lintels was designed by W.B. Baerg Truss Mfg of Saskatoon. The floor is insulated with R28 fiberglass insulation and the ceiling with R40 insulation.
- The south windows are triple glazed, argon filled, and have a double low emissivity coating designed for solar gain. East and west windows are vinyl sliders that are double glazed with a low emissivity coating designed for solar shield to keep unwanted heat out in the summer months.
- The roof is at a 12/12 pitch with deep trusses that provide plenty of attic ventilation. Soffits are a standard two feet. This keeps most of the sunlight out

of the house in the summer, because none of the windows extend down to the floor. Minimum height of the bottom of the windows from the floor is one foot.

- All building materials are readily available through local lumberyards and manufacturers.

For space heating an energy-efficient Vermont Castings Dutchwest woodstove with catalytic converter was chosen to supplement passive solar heat. The expected heat output is 10,700 to 29,500 BTU/hr. The efficiency is rated at 75.9 % and the green house gas emissions are rated at 1.4 grams/hr, which is very low compared to many other fireplaces. Combustion air is provided by a 5 inch insulated fresh air intake. Backup heat is provided by a small 30,000 BTU/hr radiant propane heater.

5 INSTRUMENTATION AND DATA COLLECTION

A standalone renewable energy system provides considerable information about the system's inputs and status, since it is important to monitor the system's performance to develop good strategies for energy conservation.

5.1 Instrumentation

The power system was monitored using a combination of monitoring functions built into the power system itself, a battery status monitor and data logging meters from which data were downloaded to a notebook PC. Figure 5.1 shows the monitoring system.

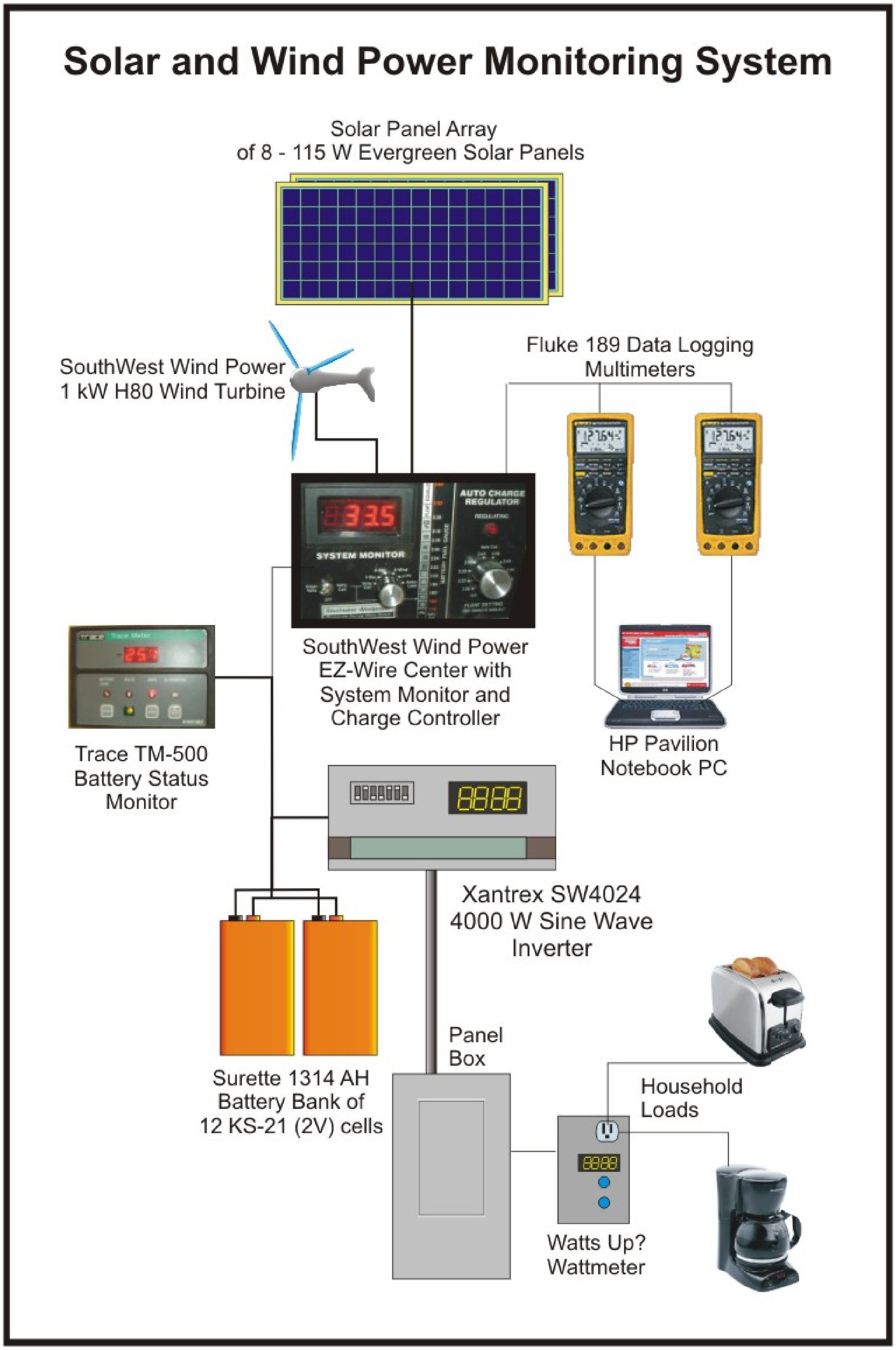


Figure 5.1 The Monitoring and Data Collection System

5.1.1 Operation and Monitoring Functions of the Solar Power System

The solar power system includes several meters to allow the homeowner to monitor the system and make adjustments to suit individual requirements.

5.1.1.1 The Inverter

The Xantrex SW4024 sine wave inverter/charger offers several modes of operation and a number of control and monitoring functions. It can operate as part of a stand-alone power system, with automatic generator start capability, or as a utility interactive inverter with the option of selling power back to the grid. A comprehensive user and setup menu provides information about the system's operation and allows the user to customize the configuration of the system.

The user menu includes a meter menu that provides a number of measurements, including the following which are relevant for this study:

- Inverter/charger Amps ac – reads the charging amps when the inverter is in battery charging mode, or the load current when the inverter is drawing from the batteries.
- Input amps ac – reads the input current from the grid or from a generator.
- Battery actual volts dc – reads the battery voltage.
- Battery TempComp volts dc – reads the battery voltage adjusted for the battery temperature which is read from a temperature sensor attached to

one of the batteries in the battery bank. This is used to set the bulk charging voltage limit for the battery charger.

5.1.1.2 The Charge Controller

The Southwest Windpower Whisper 200 System Monitor provides readings of the PV charging current, the rectified wind charging current and the battery current and voltage, using a rotary switch to select the desired reading. This is very useful but doesn't provide simultaneous readings or data logging for a detailed performance analysis.

5.1.1.3 The Amp Hour Meter

The inverter and charge regulator provide useful data about the charging and load conditions of the system but do not effectively monitor the battery state of charge. The battery voltage readings that they provide are not a sufficient indicator of the battery charge conditions.

A battery status monitor, the Trace TM500A, was installed to provide continuous measurements of the battery status which shows the battery state of charge in amp hours, the charging (or discharging) current, and the battery voltage.   One amp hour is one amp of current flowing for one hour. The battery status reading provides a basis for calculation the actual DC load used by the experimental house.

The TM500A battery status monitor has six data monitoring functions and three indicators which provide:

- State of charge shown as number of amp hours (AH), or percent of battery capacity.
- State of charge / voltage (real-time voltage level, historical high and low system voltage)
- Amps (real-time amps, total charging amps minus total load amps)
- Days since fully charged
- Cumulative amp hours
- Recharge indicator
- Low-voltage indicator
- Full-charge indicator

The indicators and parameters can be custom configured for your battery voltage and capacity and specific system requirements. The Amp hour meter is shown in Figure 5.2. The meter is showing that the battery bank is currently being charged at the rate of 25.9 amps dc.

Figure 5.2 The Trace TM500A Amp hour meter, showing 25.9 A charging current

5.1.2 Monitoring of House Performance

During the construction of the house and setup of the renewable energy system, data was manually recorded from the monitors included in the solar power system. When construction was complete and all power systems were fully operational, a data logging system was implemented to record the PV and wind charging currents. Manual meter readings were used to track the battery state of charge and the contribution of various individual loads to the overall load profile of the house.

Several options for data logging were considered. Most data logging systems use a PC to continuously record the data. However, since the house was designed to provide a cost effective renewable energy system for the residential sector, the power usage of the additional monitoring system should be kept to a minimum so that it is not necessary to purchase a larger solar power system in order to operate the monitoring system. Therefore, it was decided to use two data logging multimeters that operate on batteries and can store a full day's data in internal memory. The data is then downloaded daily to a PC.

5.1.2.1 Data Logging Multimeters and Documenting Software

In December 2005, two Fluke 189 data logging multimeters were set up to record daily solar and wind charging currents. The meters can record up to 995 intervals in internal memory. The meters are manually set up by the user to record data at a specific interval (interval events) but input events are also logged whenever the reading changes beyond the setting defined by the user. If readings are highly variable, as is the case with wind charging current, the settings for the input events must be carefully chosen so that a full day of data can be recorded within the 995 reading limit. The data is then downloaded to a PC on a daily basis.

Flukeview Forms Documenting Software was used to download and analyze the recorded data. For each interval, maximum and minimum values are recorded as well as the average value for that interval. The maximum, minimum and average values are also recorded for the full data logging period of approximately 24 hours. Data can be graphed in Flukeview Forms, along with data summaries and data tables. The data can also be exported for analysis using other software packages.

The currents were measured at the inputs to the metering section of the Southwest WindPower EZ-Wire Controller. This precedes the charge controller and dump load circuits in the controller. The charging current was calibrated as 1 Amp of charging current corresponding to 1 mV on the Fluke meter, with 0.001 mV resolution.

5.1.2.2 Wattmeter

A Watts-Up wattmeter was used to record energy usage of various individual 110 V loads. The meter provides a readout of the power and can also project the average kWh usage per month.

5.1.2.3 Anemometer with Data logger

After four months of data logging, it was found that the power output of the wind generator was considerably below what was claimed by the manufacturer for the average wind speed data that was recorded at the Saskatoon airport, adjusted for the terrain at the house site. Therefore, an NRG Wind Explorer anemometer with data logger was installed in May of 2006. The instrument provides time series wind data and a wind speed distribution with total hours and percent of time in each of 27 wind speed bins.

5.1.2.4 Other Measurements

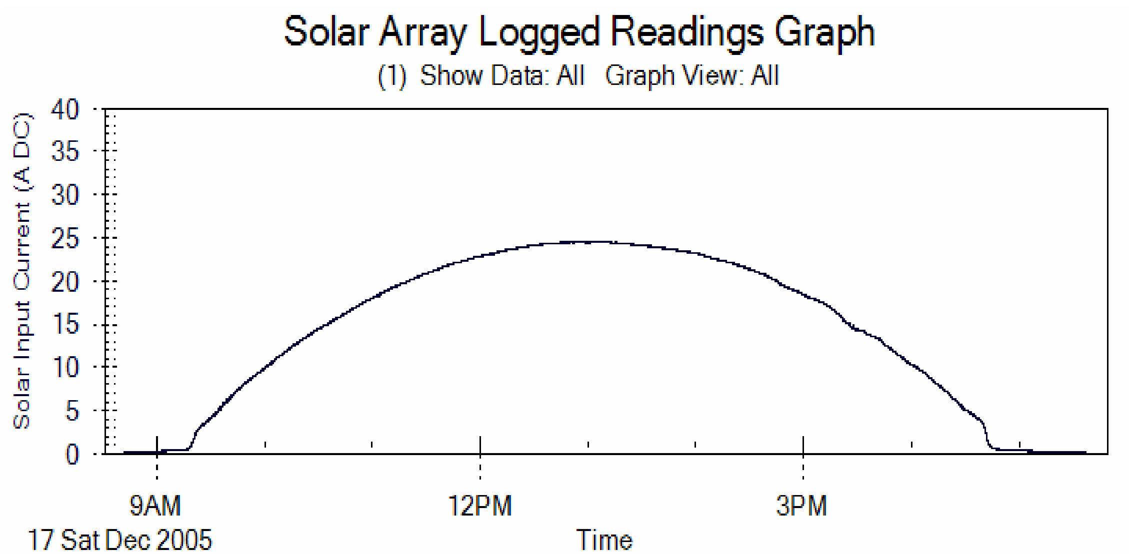
Temperatures inside and outside the house were manually recorded on a daily basis from a wireless indoor/outdoor thermometer.

5.2 Data Collection

Logged data were collected starting on January 1, 2006 for wind and solar charging currents. Logged wind speed data are available from May 23 to October 31, 2006. Manual data were recorded before this period for wind and solar charging currents, and have been recorded on an on-going basis for temperature and battery status.

5.2.1 Logged Data for Solar and Wind Charging Current

Fluke 189 data logging multimeters were installed in December, 2005 and several days of solar and wind charging current data were recorded at various interval and event settings to determine the best combination to insure that a full day of data was recorded. Figure 5.3 shows a graph and data summary for the solar charging current on December 17, 2005. This was one of very few completely clear sunshine days during the recording period. Data was recorded at 6 second intervals, directly to the laptop computer, providing consistent data for this cloudless day just before the winter solstice.



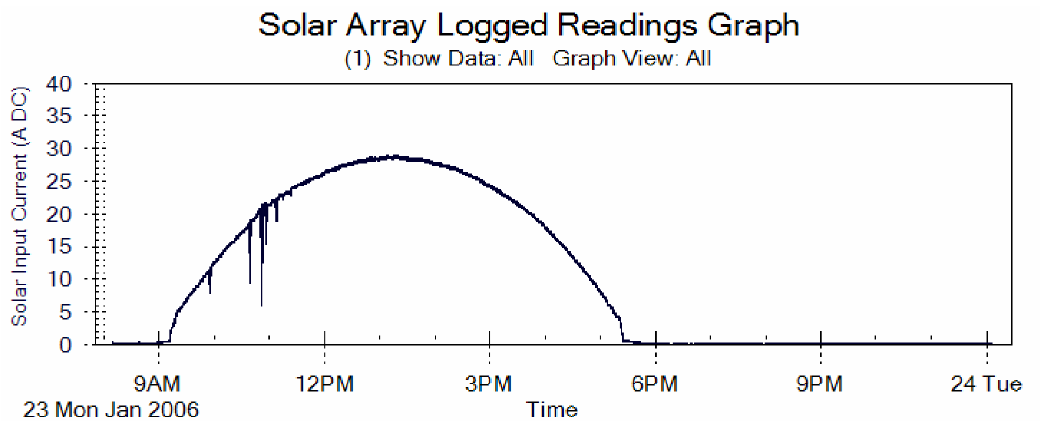
Data Summary:

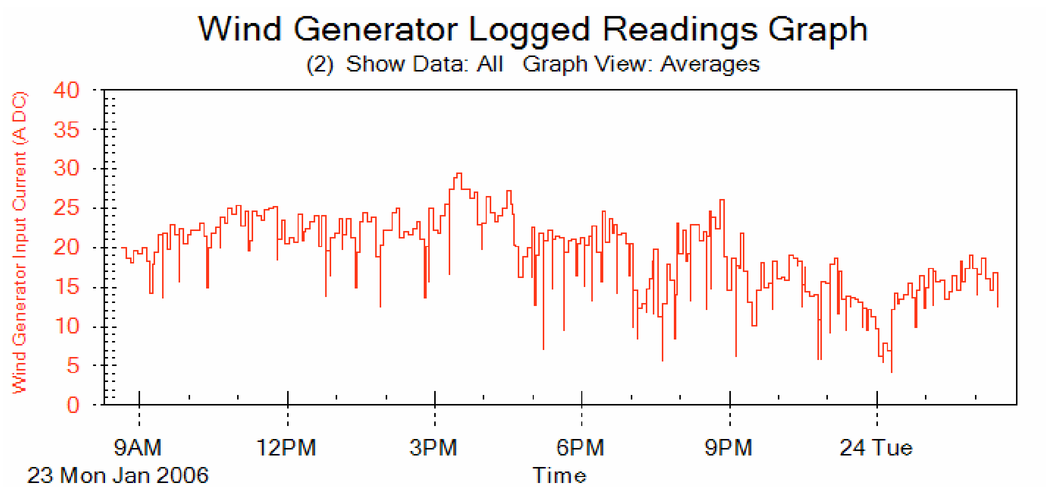
Start Time	12/17/2005 8:41:46 AM				
Stop Time	12/17/2005 5:38:07 PM				
Elapsed Time	8:56:21	Interval	0:00:06	Total readings	5364

High	**Average**	**Low**
24.563 A DC	14.330 A DC	0.157 A DC

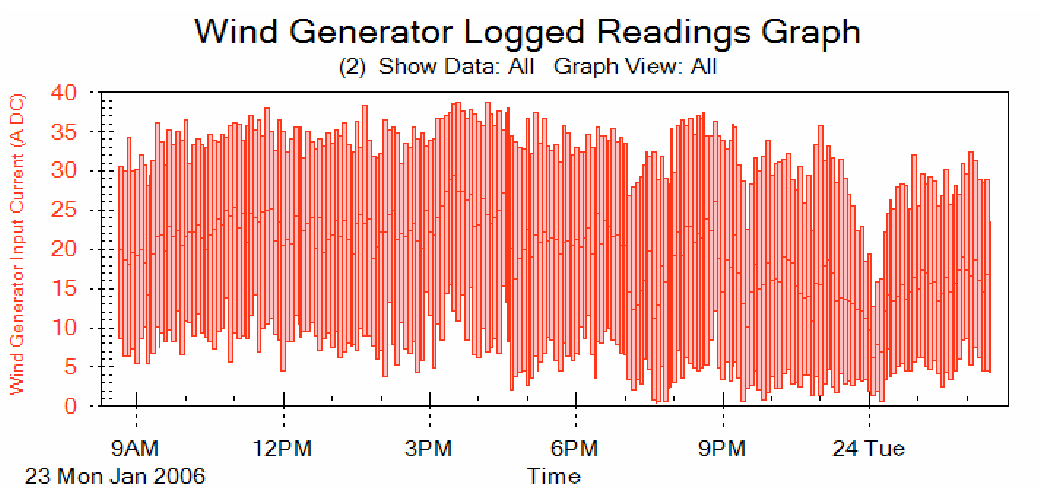
Figure 5.3 Graph and Data Summary of Solar Charging Current on December 17, 2005

Daily logged data are available starting on January 1, 2006. Figure 5.4 shows an example of logged readings graphs of the solar and wind charging currents for January 23, 2006. The charging currents for this day, recorded for an 18 hour period, represent the greatest amount of energy received, for this time period, since the readings were started on January 1, 2006.





Average wind speed is shown for each logged interval



Maximum, average and minimum wind charging currents are shown for each logged interval

Figure 5.4 Solar and wind charging currents on Jan. 23, 2006

A day for which the energy received was approximately equal to the energy used by the house loads is shown in Figure 5.5. There was very little wind on this day, and conditions were hazy, so the solar charging current was consistently lower than on a day with bright sunshine.

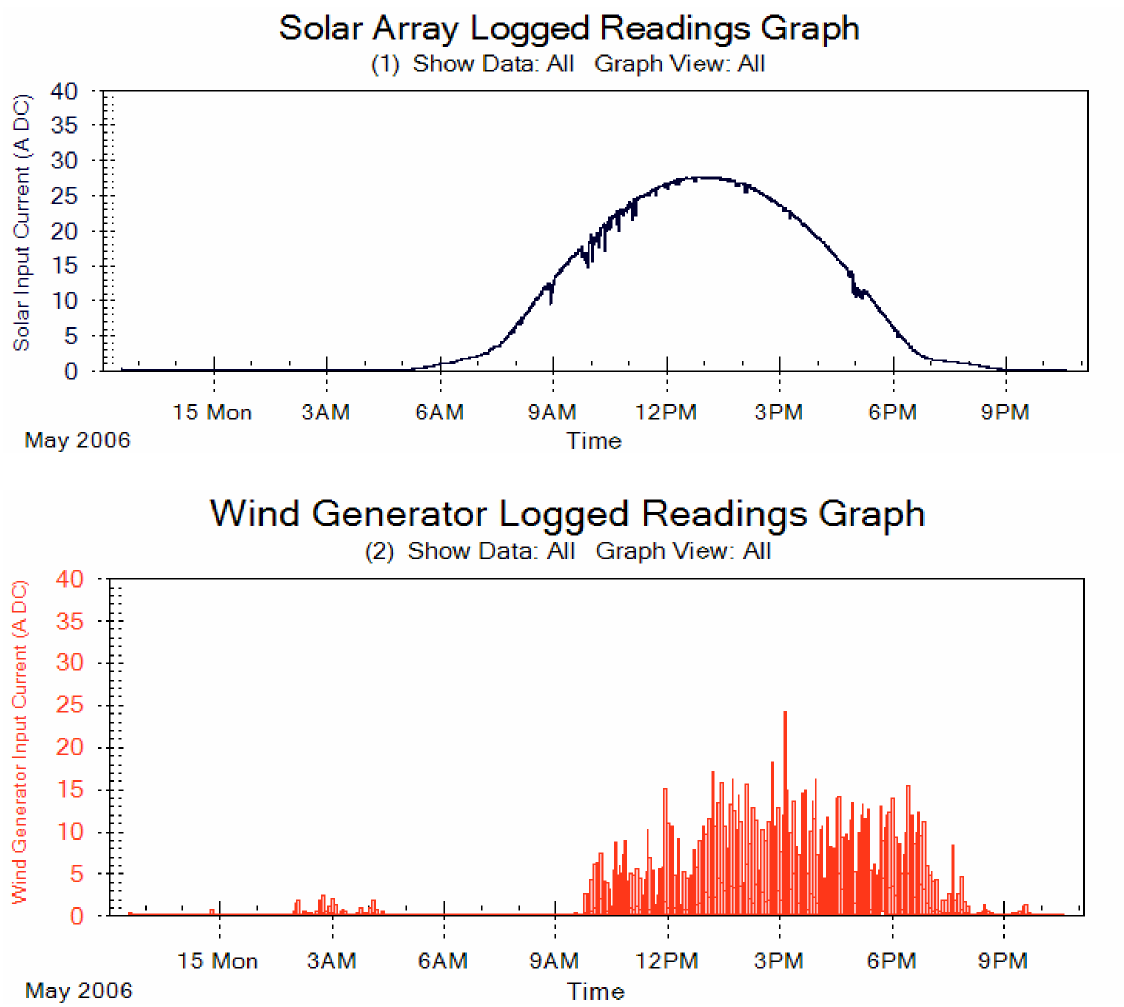


Figure 5.5 Solar and wind charging currents on May 15, 2006

Some days were recorded with no wind energy and very little solar energy due to heavy cloud conditions, often accompanied by snow or rain. Such a day is shown in Figure 5.6, for January 13, 2006 where thick clouds and snowfall for most of the day resulted in a very low amount of received energy.

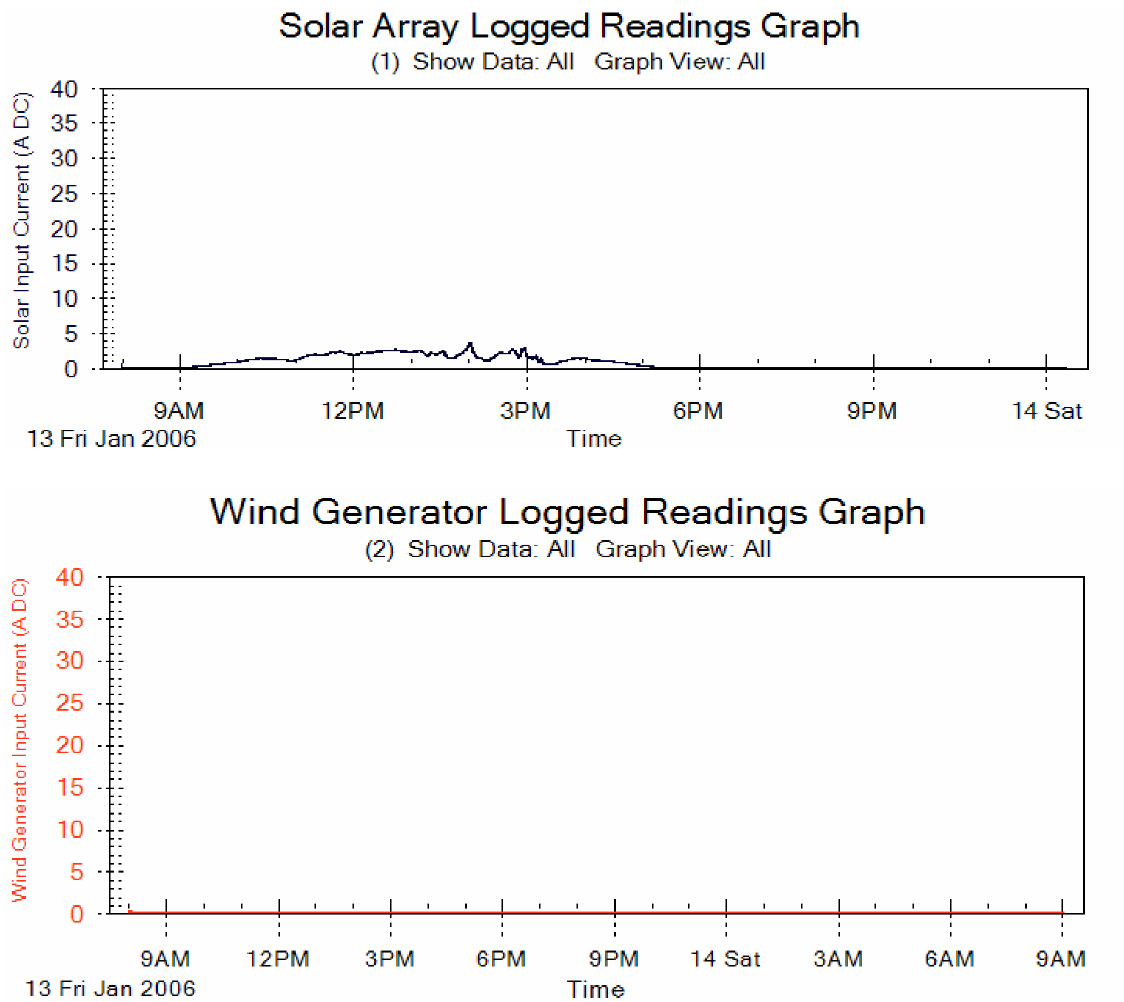


Figure 5.6 Solar and wind charging currents on Jan. 13, 2006

Figure 5.7 shows the solar charging curve for a clear sunny day close to the spring equinox, with the array angle set at 51 degrees.

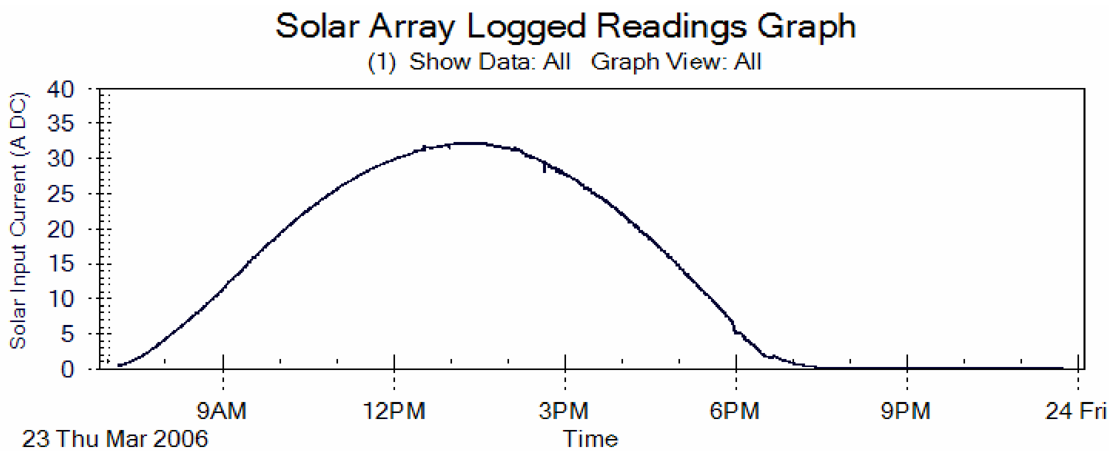


Figure 5.7 Solar charging current for March 23, 2006

Days like this were more rare than expected. Fewer than ten days between January 1, 2006 and June 30, 2006 were free of intermittent cloud.

5.2.2 Logged Wind Speed Data

The first set of results from the logging anemometer, from May 23 to August 10, 2006 is shown as a frequency distribution in Figure 5.8.

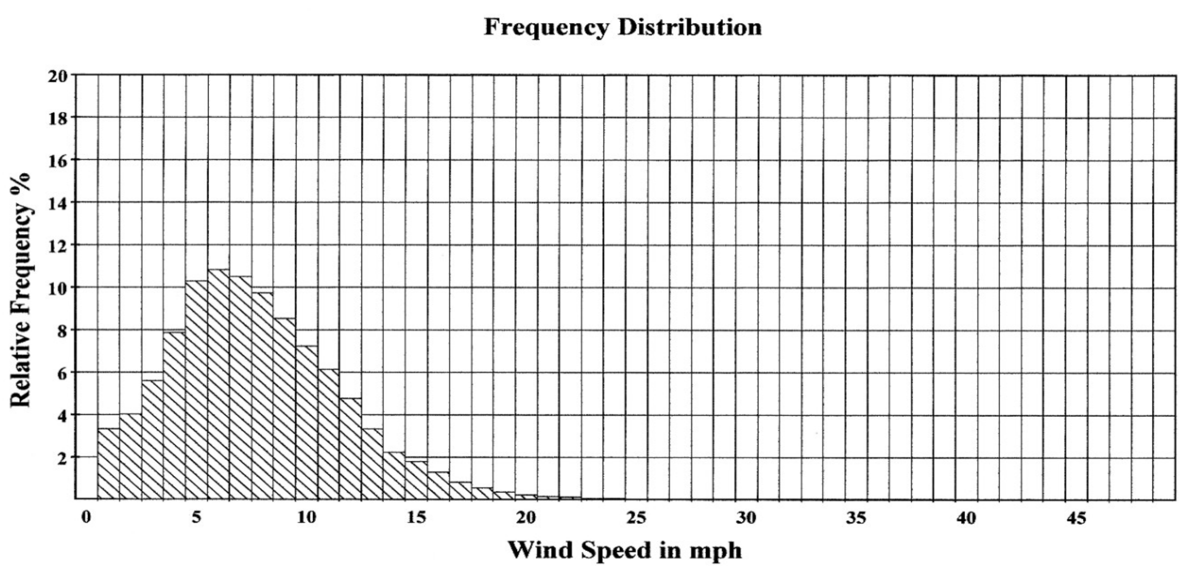


Figure 5.8 Wind Speed Frequency Distribution logged by the NRG anemometer

This shows that the wind speed distribution pattern was lower than expected in the design calculations, resulting in less charging power from the wind generator than was originally expected. The average wind speeds, calculated by the NRG program, were 9.1 mph for May (one week of data only), 7.6 mph for June, 7.5 mph for July, and 7.4 mph up to the 10th in August. The hourly averages for June are shown in Figure 5.9 below.

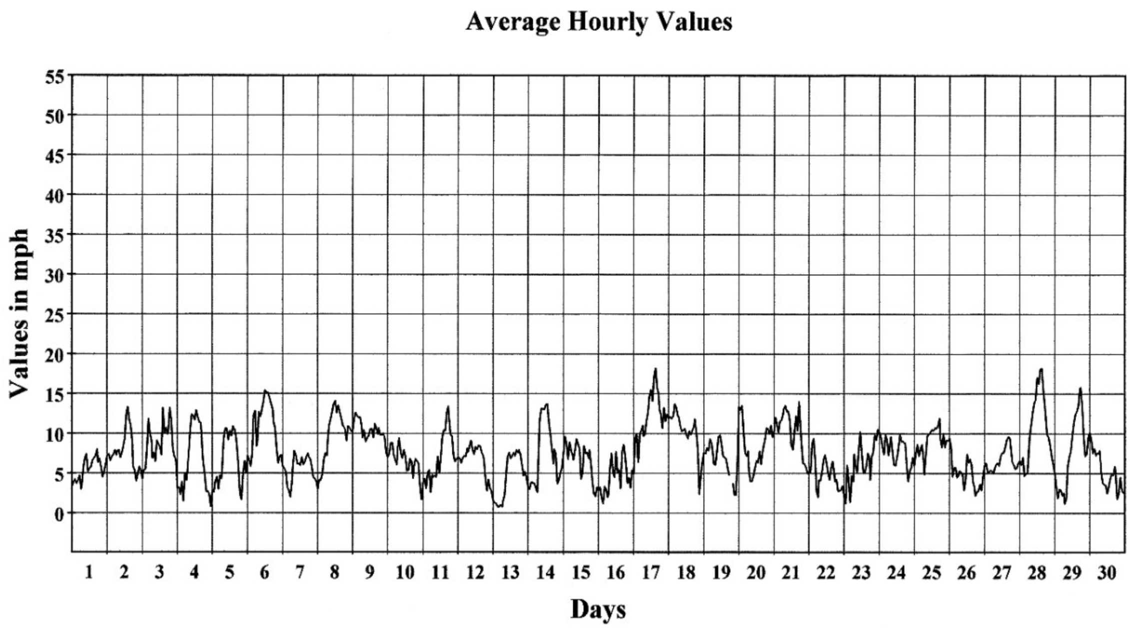


Figure 5.9 Hourly Average Wind Speeds for June, 2006

The anemometer is operating at about a 10 foot lower altitude than the wind generator. It is possible to correct for the height difference by deriving scaling factors from the data that take into account the height, time of day, season, terrain, wind speeds and temperature [33], but this is beyond the scope of this thesis. In general, wind speeds increase with increasing height above the earth's surface, so a higher tower will improve the power production of a wind generator.

5.2.3 Manual Battery Status and Temperature Data

Battery state of charge was recorded daily to track the overall load requirements of the house. A typical data set is shown in Figure 5.10 for March 2006. It was not necessary to use the backup generator during this month.

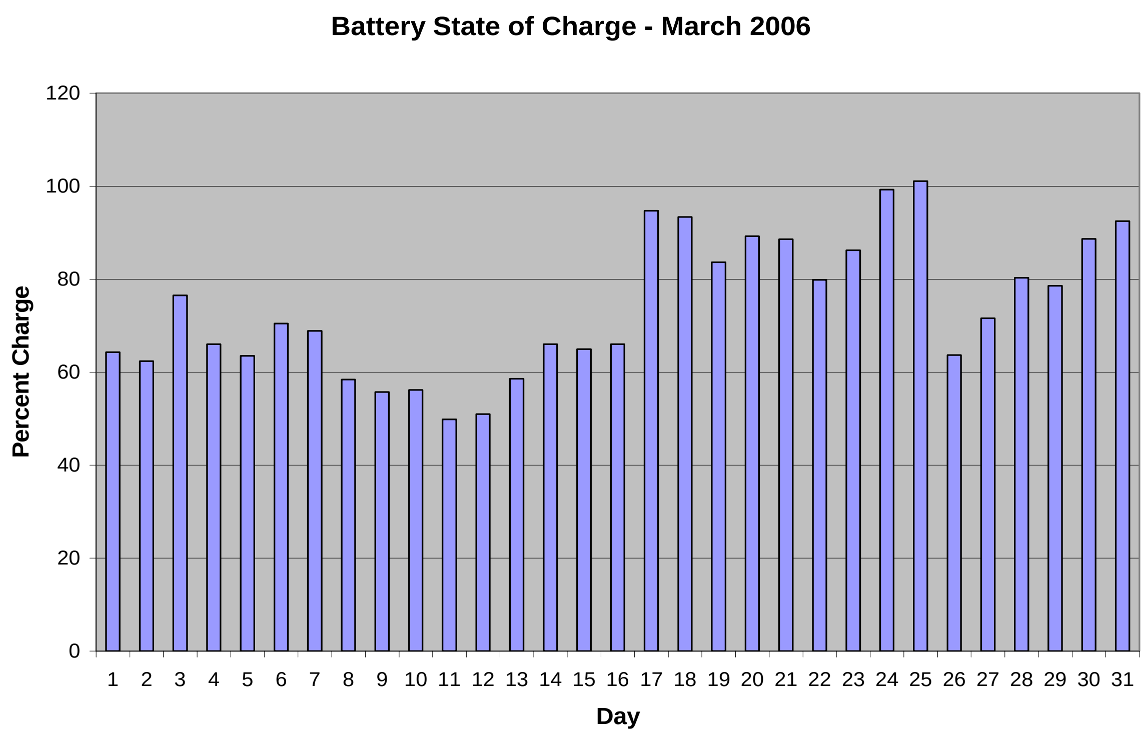


Figure 5.10 Battery state of charge, as percent of full charge, March 1 to 31, 2006

Inside and outside temperatures were also recorded daily. Table 5.11 shows temperatures recorded for October 10 – 12, 2005. These were three consecutive sunny days during which no backup heat was used in the house.

Table 5.1 Inside and Outside Temperatures on October 10, 11 and 12, 2005

Date	Time	Outside Temp (ºC)	Inside Temp (ºC)
Oct. 10	8:00	-2.1	18.9
	8:35	-0.2	18.9
	9:11	1.7	19
	9:30	3	19.1
	10:50	11.4	19.7
	11:25	12.7	20.1
	12:25	14.2	20.9
	13:05	14.6	21.4
	14:05	15	22
	14:20	15	22.2
	14:50	15.1	22.4
	16:02	15	22.9
	17:50	12.5	23.2
Oct. 11	7:07	1.4	19.5
	7:50	1.5	19.3
	8:28	2.4	19.4
	9:05	4.1	19.5
	10:37	8.2	19.8
	11:35	10.3	20.7
	12:32	11.3	21.5
	13:08	12.2	21.9
	14:50	13.2	22.9
	16:05	13.5	23.3
	16:30	13.8	23.3
	17:15	13.7	23.3
	18:00	11.1	23.3
	21:15	6	22.8
Oct. 12	6:55	-4.4	19.6
	8:25	-2.7	19.4
	10:25	4.7	19.8
	16:35	13.8	24.1
	17:07	12.7	24
	18:50	5.1	23.5
	21:50	1.6	22.7

6 PERFORMANCE ANALYSIS

The completed house, shown in Figures 6.1 and 6.2, is located on the corner of Highway 60 and St. Martin's Road just outside Pike Lake Provincial Park. The house was built on ten acres of unserviced land and no central services were connected. The house is self sufficient for power, heating, water and septic services. Power is supplied by the solar and wind power system with gas generator backup, heating by passive solar design supplemented by a wood stove and radiant propane heater, water by a sandpoint well and septic services by a fiberglass septic tank with gray water pump out to a field. Communications are by cell phone and wireless internet.

Figure 6.1 The completed house, from the southwest, on July 6, 2005

Figure 6.2 The completed house, from the southeast, on July 6, 2005

Although the solar panels and wind generator are striking features when approaching the house, the bright and sunny interior is essentially indistinguishable from a standard home. Curious visitors are amazed at how normal the inside of the house looks and operates. There are no obvious life style differences despite the extremely low energy usage for this home – about 140 kWh per month of electricity and about 80 – 100 liters per month of propane (costing about $50 plus $8 tank rental).

Figure 6.3 shows the kitchen, with standard electric fridge and gas stove and such common amenities as a coffee maker, toaster and toaster oven, slow cooker and radio.

Figure 6.3 The kitchen of the house on Feb. 18, 2005

The photos of the kitchen and the living room in Figure 6.4 were taken on a sunny January afternoon and show the sunlight entering deep into the room.

Figure 6.4 The living room on the same winter afternoon

Figure 6.5 is taken in midsummer and shows little direct sunlight, which helps to keep the house cool. Some visitors on hot summer days thought that the house had air conditioning.

Figure 6.5 The kitchen and living room around noon on April 30, 2004

Data collected for the charging system, load characteristics, heating fuel and indoor and outdoor temperature differentials provides a basis to analyze the performance of the house.

6.1 Performance of the Charging System

The daily and monthly energy, in kWh, that was received from solar and wind charging currents was calculated for each charging source from the logged data, using Equation 6.1.

$$E = \sum_{n}^{i=1} 0.001VI_i t \tag{6.1}$$

where E = total monthly energy in kWh

V = system voltage in volts

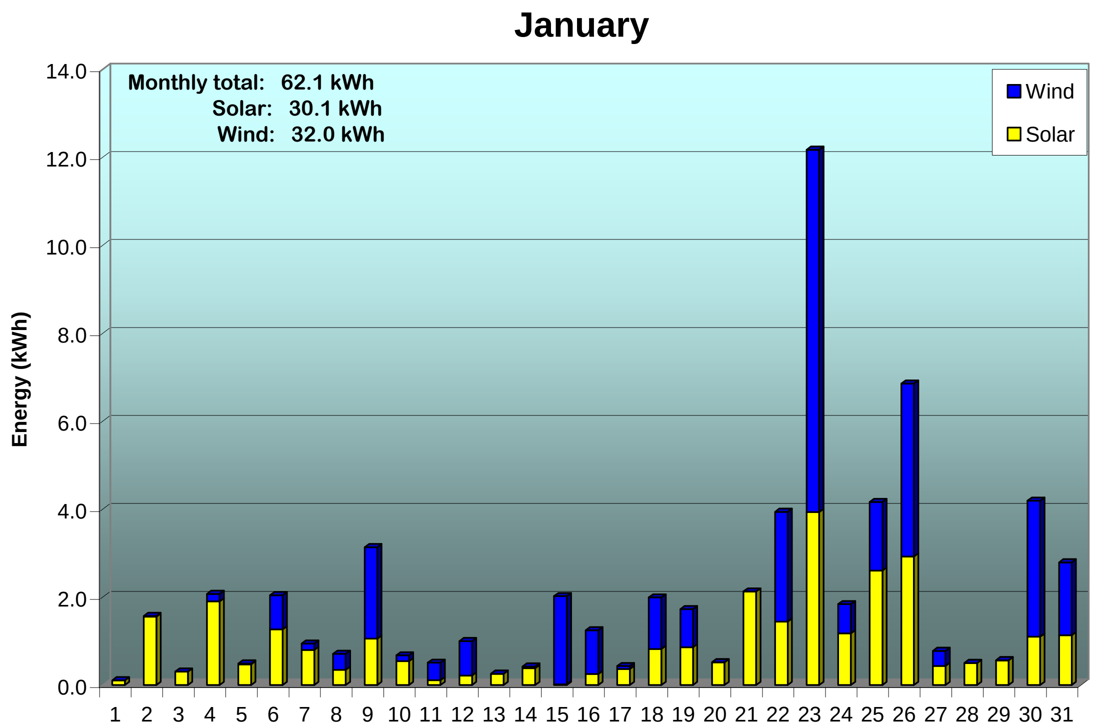
I = average charging current in amps for the day

t = time, in hours, over which the charging current is averaged

n = number of days in the month

0.001 = constant to convert watts to kilowatts.

Sample results for January and July are shown in Figure 6.6. A complete set of Solar and Wind Energy Graphs for January to December, 2006 is shown in Appendix B.



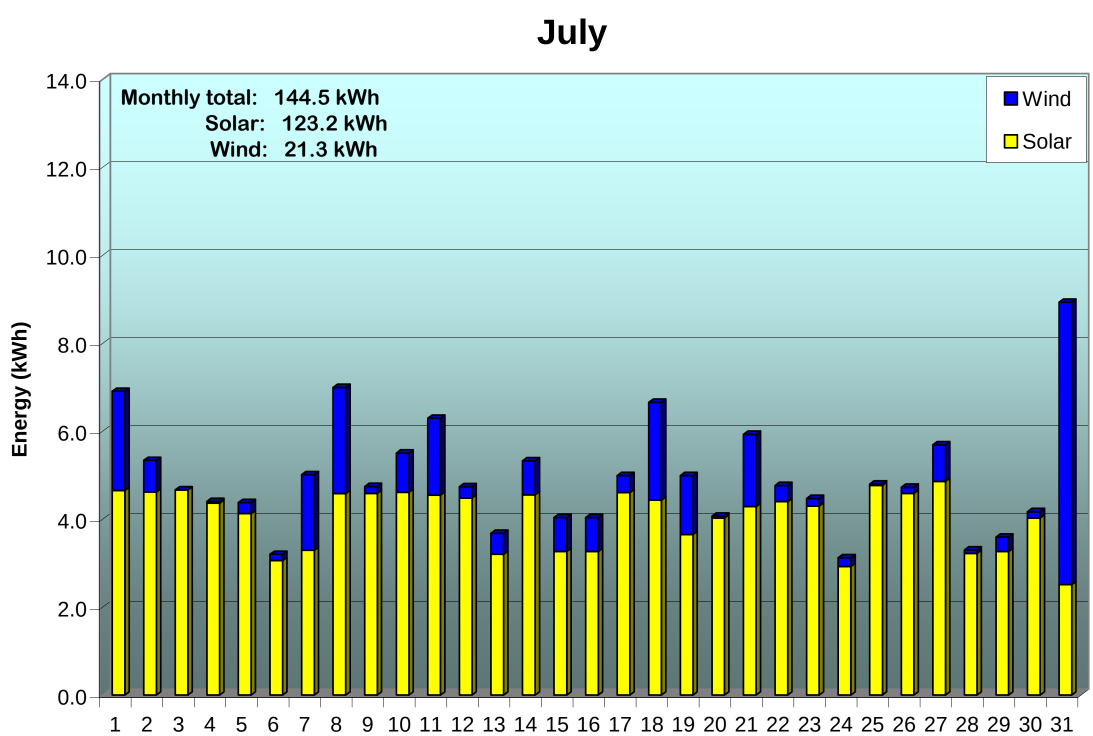


Figure 6.6 Solar and Wind Energy Graphs for January and July, 2006

A summary of the solar and wind output for 2006 is shown in Table 6.1. The summary clearly shows that 2006 has been an unusual and record breaking year for lack of winter sunshine. January is particularly dismal with only one really clear day in the entire month (January 23). Solar energy received was only 30.1 kWh, compared to the 66.3 kWh that was expected from the 10 year average, as shown in Table 4.3.

Table 6.1 Summary of Solar and Wind Energy Supplied to Batteries in 2006

Month	Solar Energy (kWh)	Wind Energy (kWh)	Total Energy (kWh)
January	30.1	32.0	62.1
February	65.4	59.4	124.8
March	101.8	40.8	142.6
April	113.7	38.7	152.4
May	93.6	50.1	143.7
June	91.7	27.6	119.3
July	123.2	21.3	144.5
August	115.3	25.0	140.3
September	81.5	33.7	115.2
October	69.6	39.5	109.1
November	49.8	49.0	98.8
December	54.4	58.2	112.6

Table 6.2 compares the expected solar energy output, based on the NASA SSE data set for average solar radiation and for the minimum solar radiation, to the energy that was actually received for the ten month period in 2006. The solar energy output was more than 25% below the expected output in January and February, and about 10% below average in May. The other months were within the expected values, with July actually having considerably higher than expected energy output.

Table 6.2 Expected and Actual Monthly Output of a 0.92 kW Solar Array with Two Tilt Angles

Month (Tilt Angle)	Expected Monthly Solar Energy at Avg. Radiation (kWh)	Expected Monthly Solar Energy at Min. Radiation (kWh)	Actual Monthly Solar Energy Supplied to Batteries in 2006 (kWh)
January (66º)	66.3	60.32	30.1
February (66º)	83.7	80.18	65.4
March (51º)	109.3	100.11	101.8
April (51º)	107.4	102.67	113.7
May (51º)	111.9	99.89	93.6
June (51º)	100.2	90.46	91.7
July (51º)	93.7	82.57	123.2
August (51º)	91.1	80.64	115.3
September (51º)	82.6	68.52	81.5
October (66º)	74.9	57.97	69.6
November (66º)	65.4	49.27	49.8
December (66º)	59.0	54.97	54.4

Comparing expected wind energy output with the actual output showed that the wind resource at the building site is considerably lower that expected.

The actual wind speed data from the Saskatoon Airport and the Anemometer data at the building site are shown in Table 6.3, with the expected output for these average wind speeds and the actual output received.

Table 6.3 Expected and Actual Monthly Output of the 1 kW Whisper 200 Wind Generator for 2006

Month	**Saskatoon Airport (m/s)**	**Expected Output at Airport (kWh)**	**Expected Output (84%) at House Site (kWh)**	**Actual Output (kWh)**
January	4.43	128	108	32.0
February	4.43	128	108	59.4
March	4.74	150	126	40.8
April	5.01	165	139	38.7
May	5.01	165	139	50.1
June	4.74	150	126	27.6
July	4.43	128	108	21.3
August	4.43	128	108	25.0
September	4.74	150	126	33.7
October	4.74	150	126	39.5
November	4.43	128	108	49.0
December	4.43	128	108	58.2
Annual Average	**3.43**	**142**	**119**	**39.6**

Table 6.4 Recorded Wind Speed Data for June to October, and Monthly Output of the Wind Generator for 2006

Month	Saskatoon Airport (m/s)	Expected Output (Airport) (kWh)	Anemometer Data at Building Site (mph(m/s))	Expected Output (House) (kWh)	Actual Output (kWh)
January	4.02	98			32.0
February	4.92	160			59.4
March	5.36	198			40.8
April	3.58	62			38.7
May	4.92	160			50.1
June	3.58	62	7.6 (3.40)	52	27.6
July	3.58	62	7.5 (3.35)	50	21.3
August	3.58	62	7.6 (3.40)	52	25.0
September	4.02	98	7.5 (3.35)	50	33.7
October	3.58	62	8.2 (3.67)	70	39.5
November	4.92	160			49.0
December	4.92	160			58.2

The actual output from the wind generator fell far short of what was expected based on the manufacturer's monthly energy output charts shown in Figure 4.4. The actual measured wind speed in June was 7.6 mph so the expected output was about 52 kWh but only 27.6 kWh was actually received. The same is the case for July, where the measured wind speed was 7.5 mph, with an expected output of 50 kWh but only 21.3 kWh was received. The wind generator needed repair at the beginning of August so was out of commission for about 3 days. This would account for some discrepancy, but not as much as was observed. Wind power output was also lower than expected because the average wind speed for most months was considerably lower than the climate normals.

The wind speed data from the anemometer was compared to the charging current data for the wind generator to see if the wind generator was actually starting to produce power at the stated cut-in wind speed of 7 mph. The data verified that it was cutting in at about 7 mph.

The wind speed distribution chart from the NRG anemometer for May 23 to Aug. 10 is shown in Figure 6.7. It is very similar to the Rayleigh Distribution shown in Figure 4.3 in Chapter 4 and used by the manufacturer to generate energy output data.

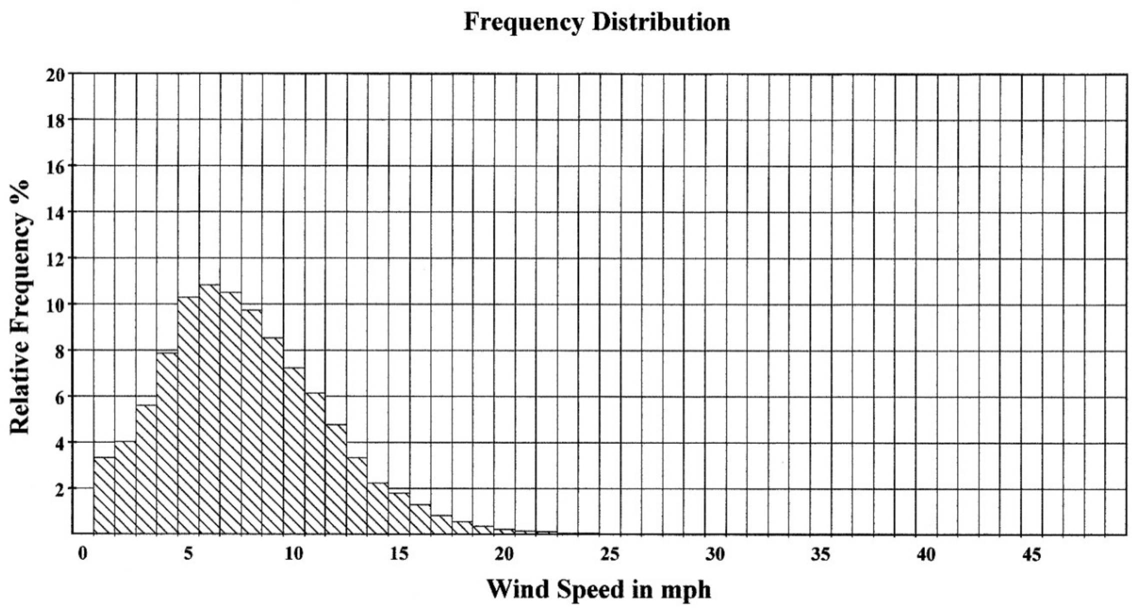


Figure 6.7 Frequency Distribution from the Anemometer for May 23 to Aug. 10, 2006

The maximum rated wind speed for the Whisper 200 is 24 mph. After this the machine "furls" which means that the generator pivots on a bolt in the split casting, aiming the propellers out of the direct wind thus protecting them from damage. The purpose of this design is that the generator should keep producing at the maximum rated power as it is furling, but this is not what was actually observed. The observed output of the generator when it was furling varied from 20 amps to 38 amps. Figure 6.8 shows the wind generator furling. It was also observed that this does not happen at exactly the maximum wind speed and is rather variable when the wind is at very high speeds.

Figure 6.8 The Whisper 200 furling in a strong gale

It is interesting to note that the frequency distribution does not show any winds above 24 mph for the time period from May 23 to August 10, but the generator was observed to furl on several occasions for an overall period of several hours over this time period. The data from the anemometer is recorded as an average for each 10 minute period. Gusts and wind speeds higher than 24 mph would therefore not necessarily be recorded. The anemometer is also about ten feet lower than the wind generator so winds would have been slightly higher at the wind generator tower height. It is also quite possible that the generator is furling at a wind speed lower than its rated maximum. Further research is needed to determine if this is the case.

There are also a number of other factors that could contribute to power output being lower than the rated output of the turbine. Some of these possible sources of power loss are:

- Loss in the conductor wires from the wind generator to the controller (length about 80 feet to the base of the tower and another 40 feet to the top of the tower)
- Pressure and temperature affect the density of the air and this can have a considerable effect on power produced - as much as 15 %. Lower air pressure and higher temperatures result in a lower air density with less power produced.
- Variations in the load and the battery state-of-charge will affect the generator output. When measuring turbine output power, measurements are only accurate for battery voltages within the charged and discharged state of the batteries. “The proposed European standard suggests measuring performance at two voltages: 112% (26.9 VDC), and 96% (23.1 VDC) of nominal battery voltage. This represents batteries that are fully charged, and heavily discharged according to IT Power, the consultants who drafted the standard. They add that voltage should be held within 2% of these values, from 26.4 to 27.4 VDC under "charged" conditions and from 22.6 to 23.6 VDC under "discharged" conditions.” [31]

The Whisper H80 wind generator has also required extensive maintenance, repair and replacement over the three year period that we have been operating the generator. It was sent back to the manufacturer in Arizona a year and four months after we installed it. It was repaired and worked for only two days before requiring repair once again.

This time, Southwest Windpower did not ask us to return the machine for repair. Instead they sent us a new wind generator – their new model, the Whisper 200, which was their replacement for the H80. The new model also comes with a five year warranty, an improvement over the two year warranty for the H80 model. However, the new Whisper 200 also failed after only a few days of operation. After many phone calls to their Technical Support personnel we were able to repair the turbine ourselves. The problem lies in the brushes and slip ring assembly, which must be very carefully aligned to prevent short circuits between the phases of the generator. We now have the expertise to repair most of the problems with the wind generator, and have had to use that expertise on two more occasions when wiring in the generator head came loose from its mountings and the wire insulation was worn through.

As can be seen from our experience, repair and maintenance issues are an important consideration with designing a hybrid power system that includes a wind generator. After all, the wind generator has moving parts and operates under very extreme weather conditions.

By contrast, photovoltaic panels have a twenty-five year warranty and require no maintenance. The panels have performed as expected and required no maintenance or repair.

In summary, solar power provided better than the expected output of 927 kWh – the solar array contributed 990 kWh of energy in 2006. The distribution of the output was not what was expected, with high energy output in the summer months and very low outputs in January and February.

The major disappointment was the wind generator, which delivered less than half of the expected output and required replacement and extensive repair (under warranty) during its first three years of operation.

Data from an anemometer, installed to find out the actual wind resource at the site, verified that the wind generator did not provide the output that was stated in the manufacturer's specifications. The wind speed was a little lower than expected, but not sufficiently to account for the significant discrepancy in performance.

Figures 6.9 and 6.10 summarize the performance results for the solar and wind charging system. Figure 6.9 shows the expected output of the solar and wind power system, and the estimated load requirements based on our initial load analysis in Chapter 4. Figure 6.10 shows the actual solar and wind output received during 2006 and the actual load requirements.

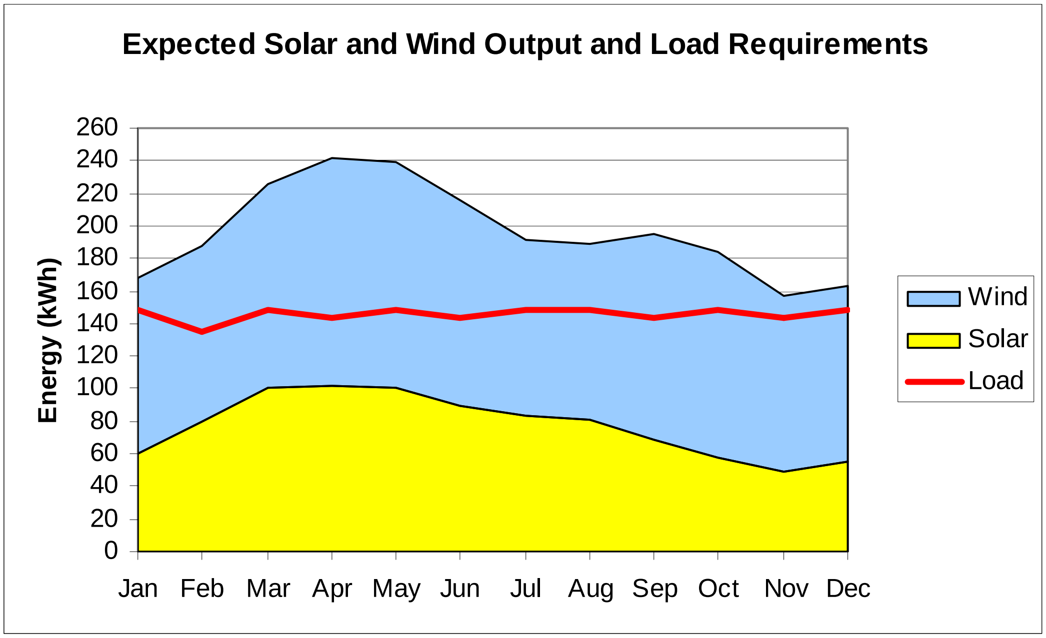


Figure 6.9 The Expected Output of the Solar and Wind Power System

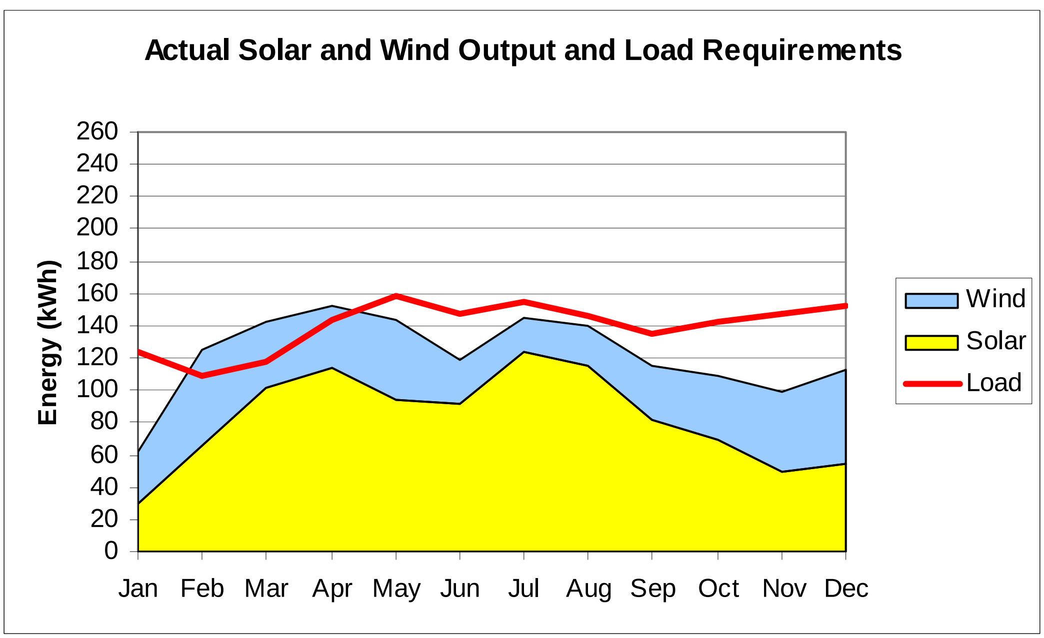


Figure 6.10 The Actual Output of the Solar and Wind Power System

The gasoline generator was used to make up the deficit for the load requirements and also occasionally for equalizing the batteries and providing a regular full charge when this was not possible from solar or wind power. The generator was operated for a total of about 240 hours at a cost of approximately $160. This was more than I had expected from the design calculations. Something that is seldom discussed when solar and wind power systems are studied is the reliability of the backup generator. It is simply assumed that it will start and run when it is needed. Perhaps this is true in warmer climates but it is certainly not true in Saskatchewan. Not only can the generator fail and need repair, but it can take many days before a qualified mechanic has time to repair it. We now own two backup generators because we found this out the hard way. Generators must have a generator shed and be regularly maintained. It is also preferable to use a large standby generator rather than a portable construction generator (as we did), although even stationary standby generators should be in a shed in our climate even if they come supplied with an enclosure.

The inverter and batteries have performed reliably over the three years that they been installed.

6.2 Household Loads

For 2006, the average daily household load for each month was calculated from the daily data for battery state of charge and the photovoltaic and wind energy received by the house charging system. The average load was calculated using Equation 6.2.

$$L_{ave} = \frac{\sum_{n}^{i=1}(SOC_i - SOC_{i-1} + E_{Si} + E_{Wi})}{n} \qquad (6.2)$$

where L = the daily household load in kWh

SOC_i = the battery system state of charge for the i^{th} day of the month

E_{Si} = solar energy input to batteries, kWh, received for the i^{th} day of the month

E_{Wi} = wind energy input to batteries, kWh, received for the i^{th} day of the month

n = the number of days in the month for which the backup generator was not started, and the battery capacity was not exceeded.

The results of this analysis are shown in Table 6.5.

Table 6.5 Average Monthly Household Loads for 2006

Month	Average Daily Load (kWh)
January	4.0
February	3.9
March	3.8
April	4.8
May	5.1
June	4.9
July	5.0
August	4.7
September	4.5
October	4.6
November	4.9
December	4.9

A 7 cubic foot Danby freezer was added to the household loads on March 31. The freezer is rated at 248 kWh/year, but measurements with the Wattmeter showed that the actual energy consumption is 444 kWh/year. Starting in May, I spent many more than the estimated number of hours using the computer and the internet to complete this thesis and we also watered some fruit trees, increasing the demand on the water pump. These three additional loads account for the higher average daily load values, starting in April.

Loads in January, February and March were considerably lower that expected from the load analysis because the estimated usage for some of the appliances turned out to be higher than the actual usage. For example, we have only used the electric frying pan two or three times during this period.

6.3 Thermal Performance

A 400 liter propane tank was installed at the house site on October 20, 2003. The propane fuel is used for the backup propane heater, the on demand hot water heater, and the cook stove. All propane fills since the installation of the propane tank are shown in Table 6.6.

Heating the house has been quite economical. Propane was delivered four times during 2006 with the last fill just before the end of the year. The total cost of propane for 2006 was approximately $600, based on the fills for January, February, March and December. The annual tank rental is $96. This is about $58 per month, which is a very reasonable cost for heating a 1000 square foot home, heating the water and providing the cooking fuel. This would indicate that the passive solar design is working very well, resulting in heating fuel costs substantially below what most homeowners would pay. A typical monthly bill for natural gas for a house of comparable size is around

$1200 per year, and this does not normally include the cook stove which is usually electric.

Table 6.6 Propane Tank Refill Dates, Propane Volumes, and Costs

Refill Date	Vol. of Propane (l)	Cost
Oct. 20, 2003	380	$206.96
Jan. 9, 2004	288.6	$157.18
Feb. 6, 2004	246.1	$134.03
June 3, 2004	312.2	$160.01
Nov. 2, 2004	281.7	$174.52
Jan. 24, 2005	331.8	$181.77
Mar. 31, 2005	297.4	$177.89
Sept. 20, 2005	239.4	$159.08
Jan. 11, 2006	274.1	$190.34
Feb. 22, 2006	335.4	$200.61
March 29, 2006	293.1	$175.51
Dec. 21, 2006	286.6	$191.09

However, propane usage was actually higher in 2006 than in previous years for two reasons. One reason is that we installed a new Comfort Glow ventless 30,000 BTU/hr radiant propane heater that required less space and had a higher efficiency rating than the old 20,000 BTU/hr WAIT heater. It was installed as specified, but the thermostat on the unit did not seem to properly control the firing sequence for the burner. It was observed that the burner kept firing even when the room temperature exceeded the set temperature for the thermostat. We didn't realize this for some time and believe the solution to the problem is to move the thermostat to a different location further away from the heater itself. Results over winter of 2006/2007 should show whether this solves the problem. The other reason the usage is higher is that January had much less than the normal amount of sunshine so the passive solar heating contribution was also much less. This winter we also worked long days and often didn't arrive home until after seven o'clock in the evening. This meant that we didn't light the woodstove early in the evening, as we had in previous winters. Normally we burned about one and a half cords of wood over the winter season, but this season it was only about one cord. Much of the firewood was deadfall from the acreage, collected over the winter, so we do not have an accurate value for the number of cords used.

It is also interesting to note that the $175 fill on March 29 has lasted for over eight months, being used almost exclusively for water heating and cooking. This means that water heating and cooking only cost about $30 per month, including the cost of the tank rental. This shows that an on demand water heater is a more efficient option than a tank system and also shows that cooking with propane is quite efficient. Incidentally, the propane fills include the 20 lb. tanks used for the barbecue.

We have also had the opportunity to observe the impact of thermal mass on the passive solar design of the house. When the house was still under construction during the early part of the winter, it would become so hot on sunny days in November and December that we would open doors or windows to keep the house comfortable. Inside temperatures topped 26° C, with no contribution from the woodstove or backup heater. Once the house was completed, the inside temperature was generally 20 - 24° C under similar conditions. This shows the contribution of solar thermal mass to even out the temperature in the home. The overall mass of gyproc, hardwood and brick facing absorbed some of the heat from the sun, imparting less heat to the air during the day.

The heat stored in the walls and floors was radiated into the air after sundown. This effect, combined with the construction methods of the house, resulted in fairly stable inside temperatures even when there was no heat source used in the house.

The heat retention capability of the house is shown in Figure 6.11 which follows the temperatures inside and outside the house on three consecutive sunny days in October, 2005. For these three days the woodstove was not lit, and the propane heater had been removed because a new one was to be installed, so there is no heating source other than passive solar heating. Figure 6.11 shows that the daily inside temperature fluctuation was less than 5°C for three sunny days in October when the outside temperature fluctuated by 20.5°C, from -4.4°C on one of the days to 15.1°C on another.
This data was manually recorded by the occupants.

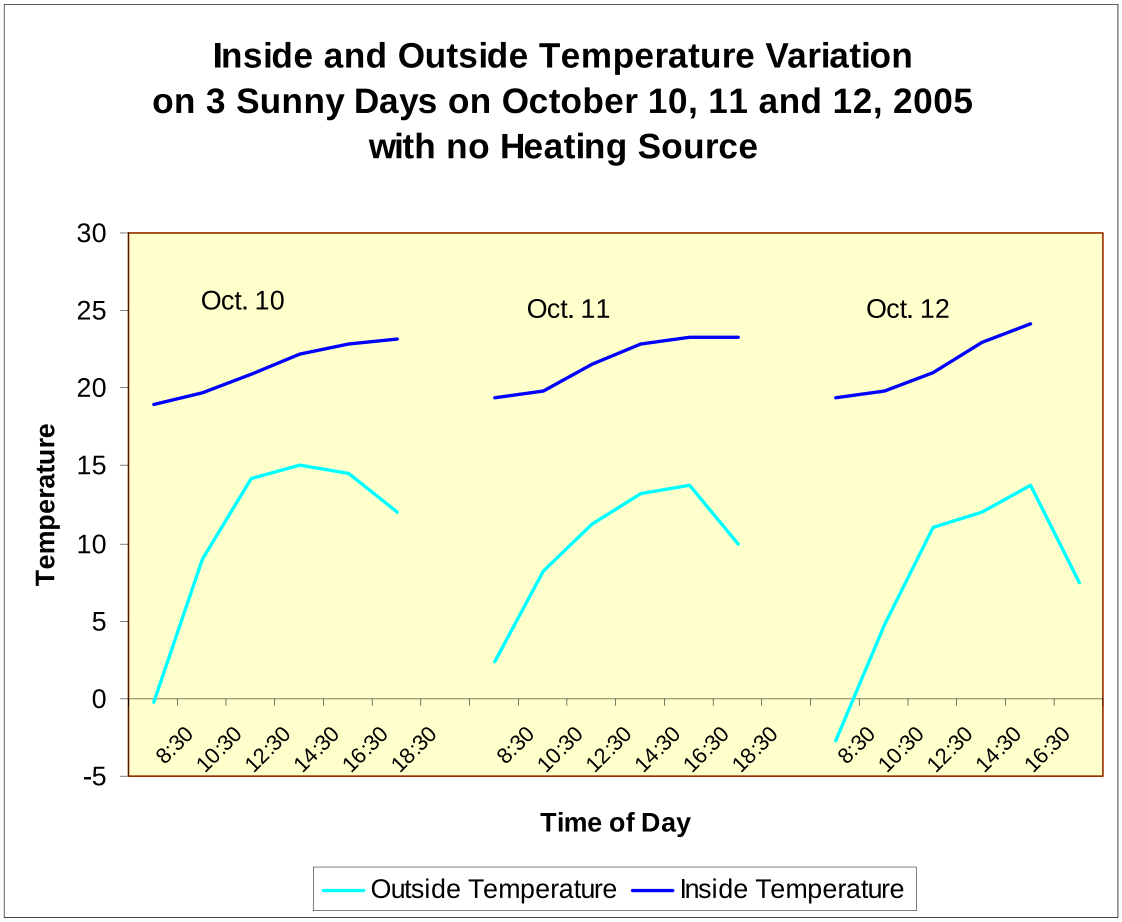


Figure 6.11 Comparison of Temperatures Inside and Outside the House

During the winter it was observed that, on sunny days, the house would maintain an inside temperature of 20 to 23 degrees Celsius with no heat source other than the passive solar heating from the sunlight.

7 CONCLUSIONS

The design and construction of a small experimental house before proceeding with an expensive home incorporating unfamiliar design features, has proven to be very valuable. Our experiences building and living in the home and collecting data on its operation have changed our ideas about the next renewable energy building project. Overall, the house performance was rather different from our expectations, with the solar array performing better than expected and the wind generator producing substantially less than calculations indicated. This meant using the backup generator more than we had expected.

Our lifestyle was not much different from anyone else's, except that we are in the habit of turning things off when we are not using them. Our results show that the power system is economically feasible for energy efficient homes built on unserviced sites that are somewhat more remote than our site, and that passive solar design is an effective way to reduce energy consumption.

7.1 Implications for Future Designs

The results of this experiment have provided insight into the complexities of assessing a site for solar and wind resources and the challenges of designing for them. A good design must account not only for the weather but also the limitations of the equipment and the maintenance issues involved. Backup systems are also part of the design and must be sized appropriately and their reliability factored in. Having your own power system gives you independence but also makes you responsible for the successful operation of your system. This provides you with an understanding and appreciation of the technology and the resources that supply your daily needs.

The experimental results raise serious questions about the economics of using wind power, especially at the present building site. If the cost of the wind generator and tower had instead been invested in six more solar panels, the output for 2006 would have been 1733 kWh instead of the 1465 kWh that was received from the combined wind and solar system. Figure 7.3 shows how this output would have been distributed over year.

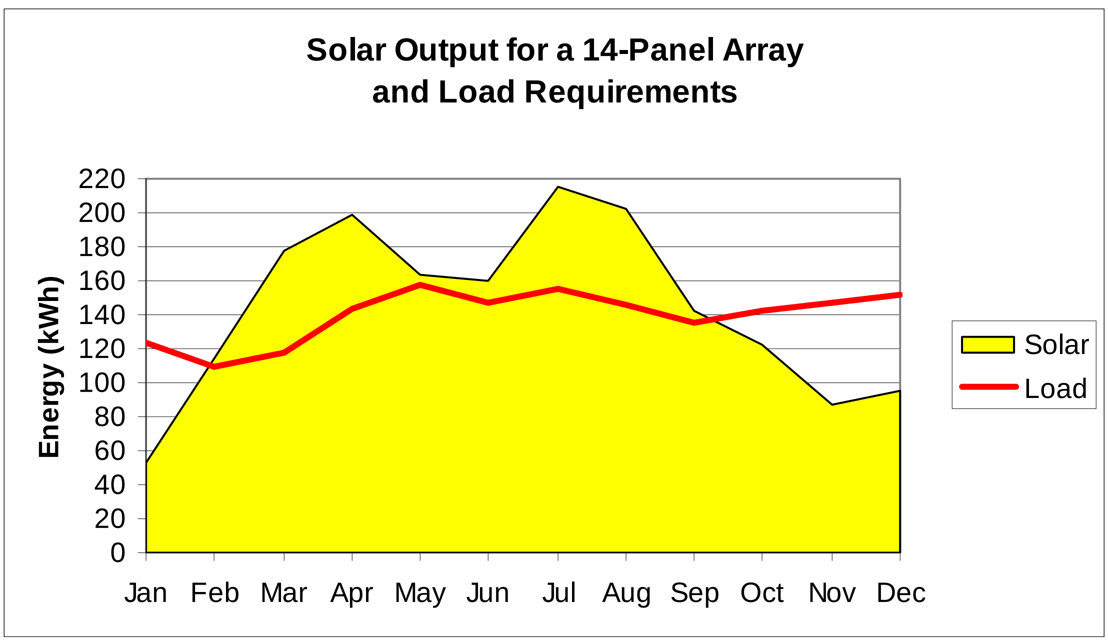


Figure 7.1 2006 Solar Output Calculated for a Strictly Solar, 14-Panel Array

This indicates that for our location, with its rather poor wind resource, a strictly solar system might be a better choice.   However, part of the problem was that the wind generator output was less than was claimed for the wind conditions at our site. If the wind generator had performed closer to expectations, the load requirements would have been met for most months where there was actually a deficit.

A better wind generator and two more solar panels would be a good solution that would meet the load requirements for most of the year. This solution would cost about $2000 more that the present system for the two extra panels. A local company, Raum Energy, is developing a wind generator that is robustly designed for Saskatchewan conditions and is optimized to produce more power at the lower wind speeds that are common here. Cost is expected to be comparable to the Whisper 200. They expect to have a test model in a few months and we will be participating in the testing of the wind generator, installing it temporarily at our experimental house. Figure 7.4 shows the output of our present system with two extra panels and a wind generator output that is 160% of what was actually received, since this is closer to the expected values at those wind speeds.

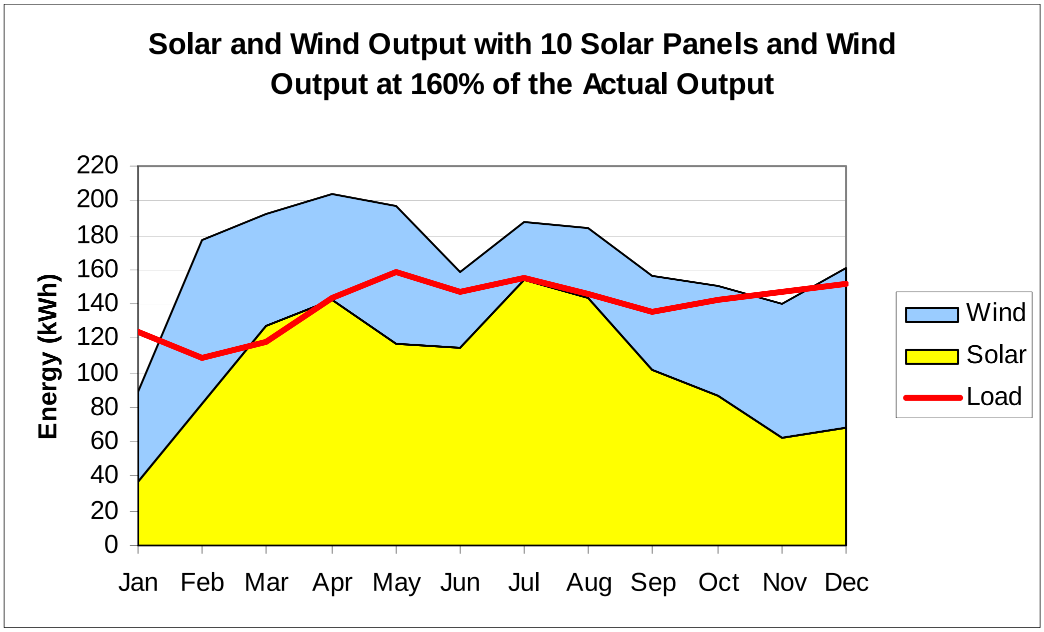


Figure 7.2 An Alternate System for the Experimental House

A system of this size would need very little generator backup, and still be a reasonable cost.

Another option would be to use a smaller wind generator that has a lower cut-in wind speed. Generally the smaller wind generators also have a lower peak power and wind speed but this may more closely fit the wind frequency distribution for our area.

7.2 The Use of Renewable Energy in Saskatchewan

At the present time, a renewable energy power system is not an economically feasible option in Saskatchewan for off-grid systems in non remote areas where grid connection costs are less than about $20,000. This is due to the low cost of purchased electrical power and the lack of any incentives for renewable energy use.

The environmental benefits of using renewable energy are well established, but the economic costs show that financial assistance or incentives are needed to make this feasible for Saskatchewan homeowners. Ontario is the first province in Canada to take a step in this direction with its introduction of the standard offer contract that will pay independent solar power producers $.42 per kWh sold to the utility grid. However, the RETScreen analysis in Table 7.1 shows that this does not improve the financial viability enough to make it worthwhile. The analysis is performed using the same input parameters as the experimental house but without the credit for the $10,000 grid connection and a buy-back rate of $.42/kWh is included.

Table 7.1 Financial Feasibility for a Feed-in Tariff of $.42/kWh

Financial Feasibility		
Pre-tax IRR and ROI	%	0.3%
After-tax IRR and ROI	%	0.3%
Simple Payback	yr	37.3
Year-to-positive cash flow	yr	28.2
Net Present Value - NPV	$	(13,597)
Annual Life Cycle Savings	$	(801)
Benefit-Cost (B-C) ratio	-	0.56

Without the $10,000 grid connection costs, the ROI and payback is actually poorer than for the experimental house. Clearly, a rebate to offset the initial capital costs is necessary to make the use of renewable energy financially feasible. If ROI and payback period are to be the main criteria for a homeowner deciding to use a renewable energy system then this rebate would have to be over $10,000, as indicated by the financial analysis in Chapter 4. However, most homeowners interested in a renewable energy system are not only interested in economics but also in the environmental benefits and independence, and are willing to pay somewhat more for these benefits.

The Saskatchewan government is starting to look at this issue. In December, 2006 Peter Prebble published a first report on renewable energy development in Saskatchewan, which looks at how to make Saskatchewan a leader in renewable energy development [37]. He describes possible rebate and incentive plans, net metering and feed-in tariffs, as well as other issues for promoting renewable energy and energy conservation.

Another part of the mix is the backup generator which presently uses fossil fuels, but renewable fuels such as biodiesel offer hope that renewable fuels may soon be available for the backup systems as well. This will improve environmental benefits, but not reliability. The best way to improve the reliability of a renewable energy system would be through grid-connection but, without incentives in place, financial feasibility is sacrificed for greater reliability.

After living with our renewable energy system for three years, we have found that the cost effectiveness of the power system, which initially was one of our primary concerns, is no longer as important to us. We enjoy using clean renewable energy, being independent and self sufficient, and watching our meters to see what the sun and wind are providing for free.

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APPENDIX A

A Comparison of Four Small Residential Wind Turbines (taken from [28])





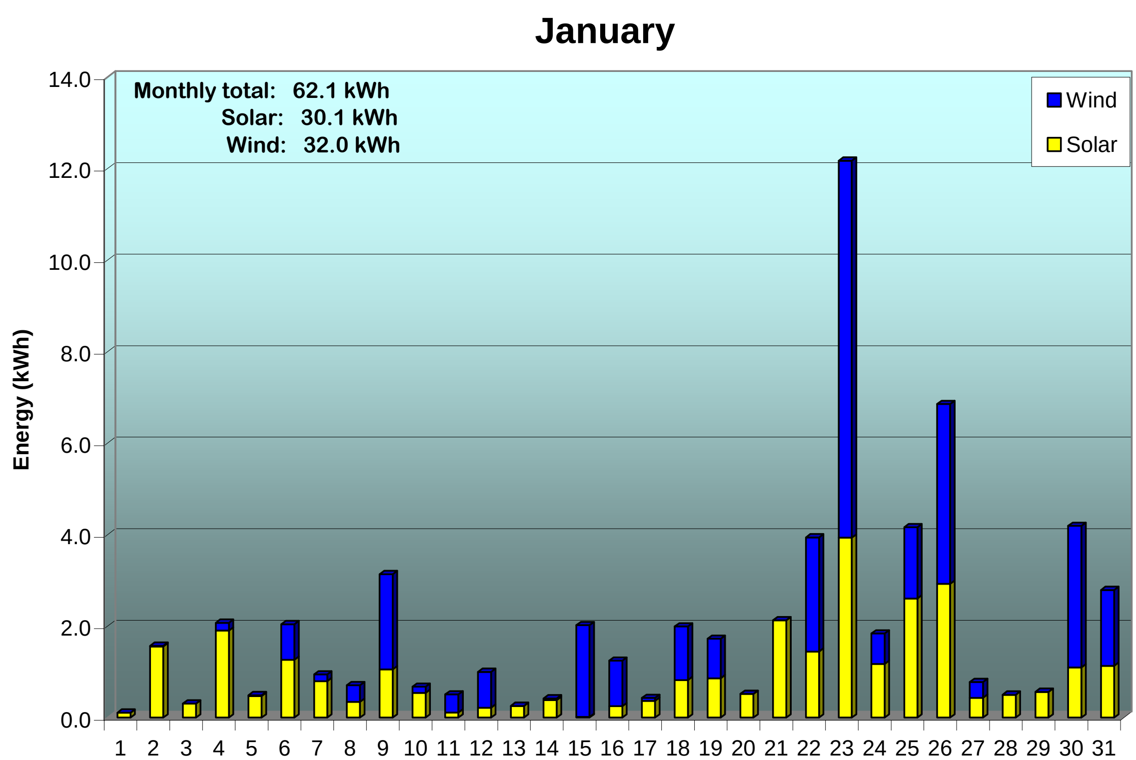
Model	Whisper H40	Whisper H80	WT 600	AWP 3.6
Manufacturer	Southwest Windpower	Southwest Windpower	Proven Engineering	African Windpower
Swept area, square feet	38.5	78.5	55.4	109.0
Rotor diameter, feet	7.0	10.0	8.4	11.8
Cut-in wind speed, mph	7.5	7.0	6.0	6.0
Rated wind speed, mph	28.0	26.0	22.5	25.0
Rated output, watts	900	1,000	600	1,000
Peak output, watts	900	1,000	700	950@24 V; 1,050@48 V
Maximum design wind speed, mph	120	120	145	100 Experienced
Rpm at rated output	1,150	900	500	350
Blade material	Injection molded plastic	Injection molded plastic	Polypropylene	Fiberglass
Tip speed ratio (TSR)	10.3	13.4	6.7	5.5
Generator type	PM 3 AC	PM 3 AC	PM 3 AC	PM 3 AC
Governing system	Angle governor	Angle governor	Hinged blades	Side facing
Governing wind speed, mph	28.0	26.0	22.5	25.0
Shut-down mechanism	Dynamic brake	Dynamic brake	Disc brake optional	Dynamic brake
Tower top weight, pounds	47	65	154	250
Lateral thrust, pounds	150	250	450	250
Battery system voltages	12 to 48	12 to 48, or 220	12, 24, or 48	12, 24, 48, or 220
Controls included in cost	Controller & dump load	Controller & dump load	Battery controller	Battery controller
Utility intertie	With batteries	With batteries	With batteries	With batteries
KWH / month @ 8 mph	30	60	42*	75
KWH / month @ 9 mph	45	90	66*	105
KWH / month @ 10 mph	65	125	83*	130
KWH / month @ 11 mph	80	160	113*	168
KWH / month @ 12 mph	105	190	124*	192
KWH / month @ 13 mph	125	215	146*	226
KWH / month @ 14 mph	155	265	167*	246
Cost, US$	$1,495.00	$1,995.00	$3,338.00	$2,214.00
Cost per sq. ft. swept area, US$	$38.83	$25.41	$60.25	$20.31
Cost per pound, US$	$31.81	$30.69	$21.68	$8.86
Weight per swept area, pounds	1.22	0.83	2.78	2.29
Weight per TSR, pounds	5	5	23	45
Years in production	3	3	5	3
Warranty, years	2	2	2	2
Routine maintenance	Annual inspection	Annual inspection	Annual inspect & grease	Annual inspect & grease
Notes		HVLV available	Downwind	HVLV available

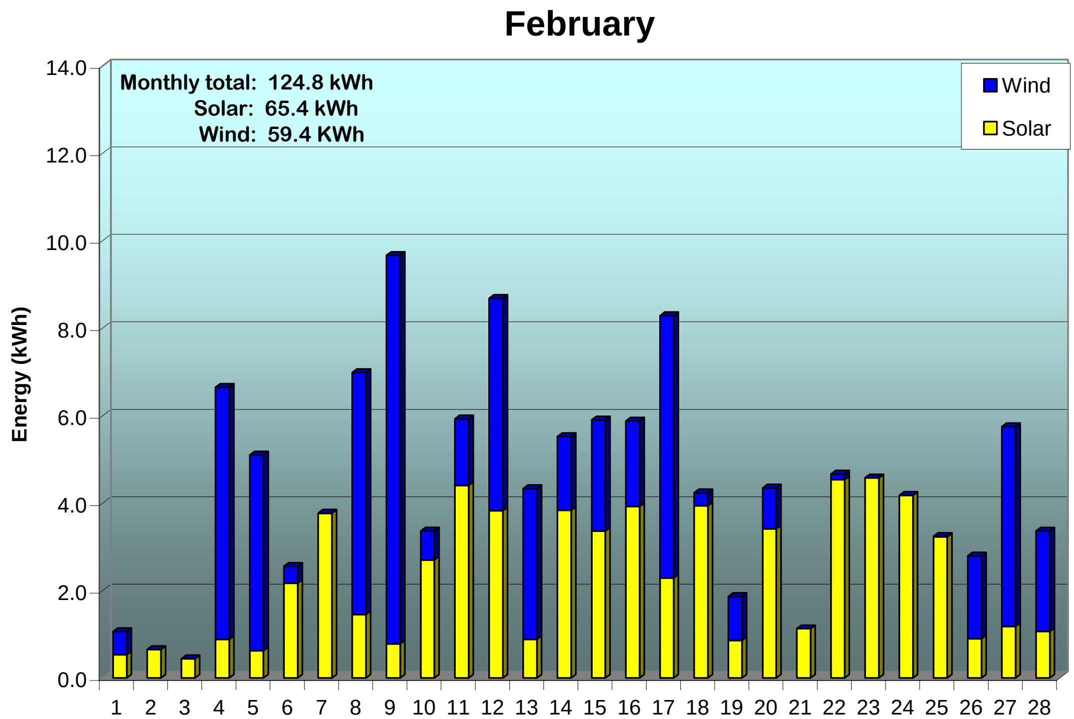
* Estimated by author

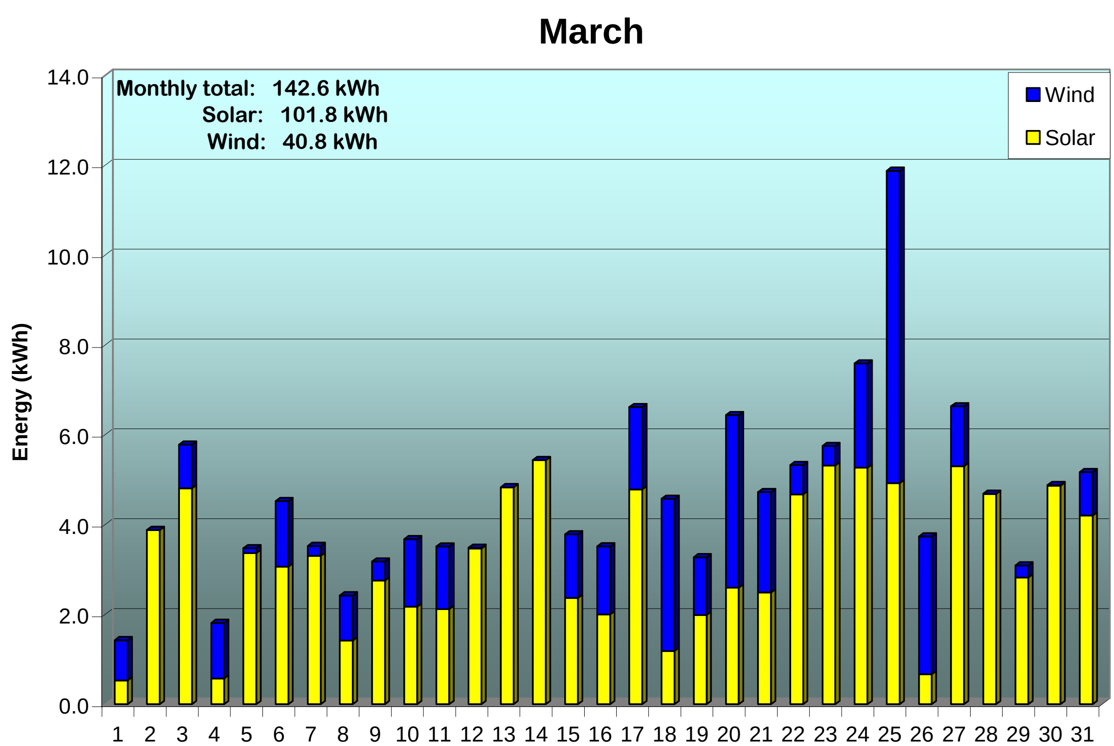
APPENDIX B

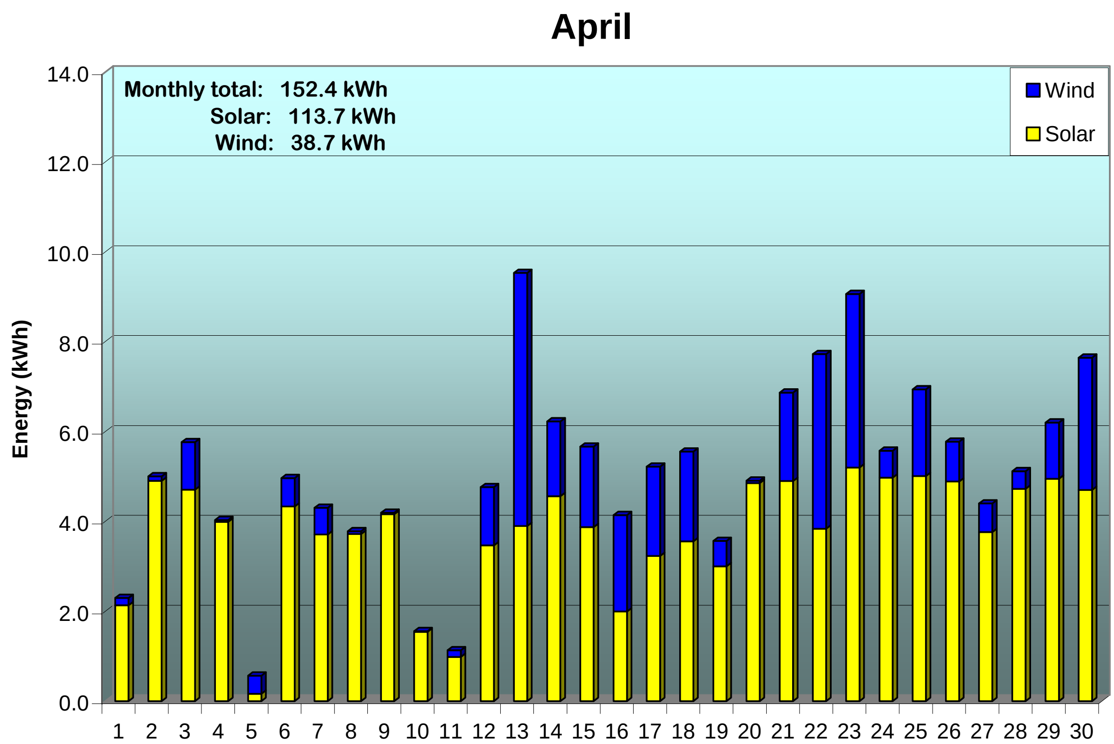
Solar and Wind Energy Graphs for January to October, 2006

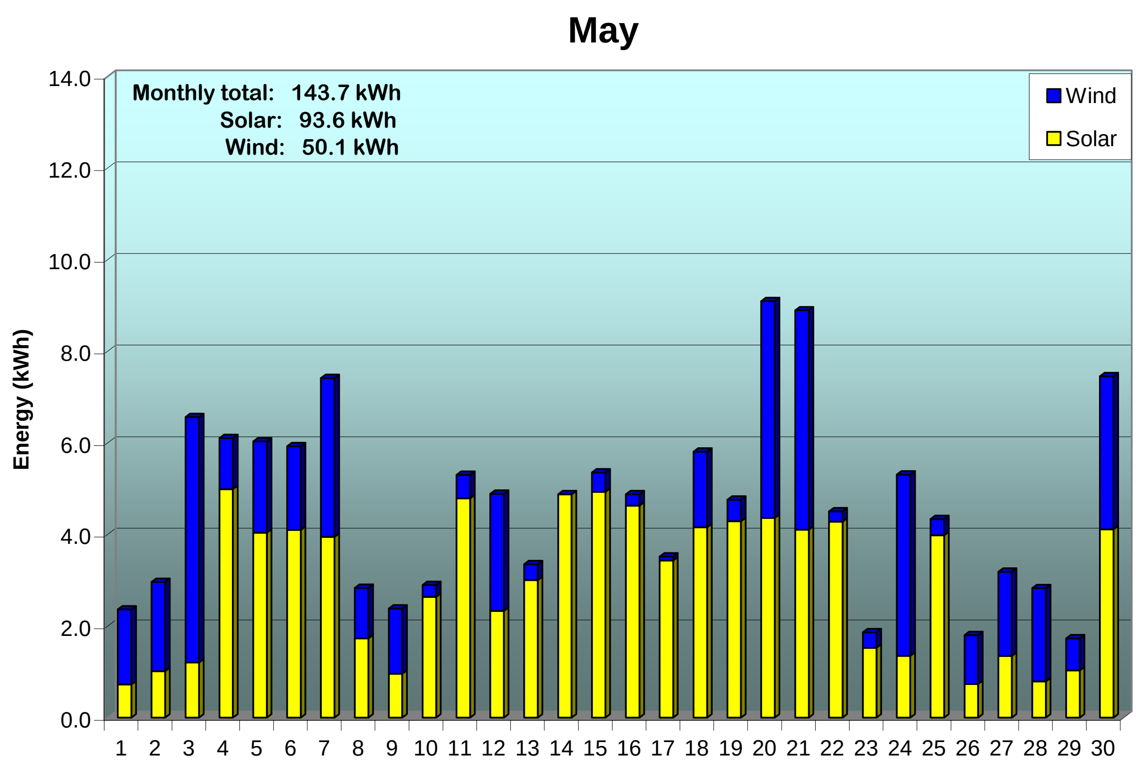
The graphs below show the solar and wind energy received daily for each month in 2006, from January to October.

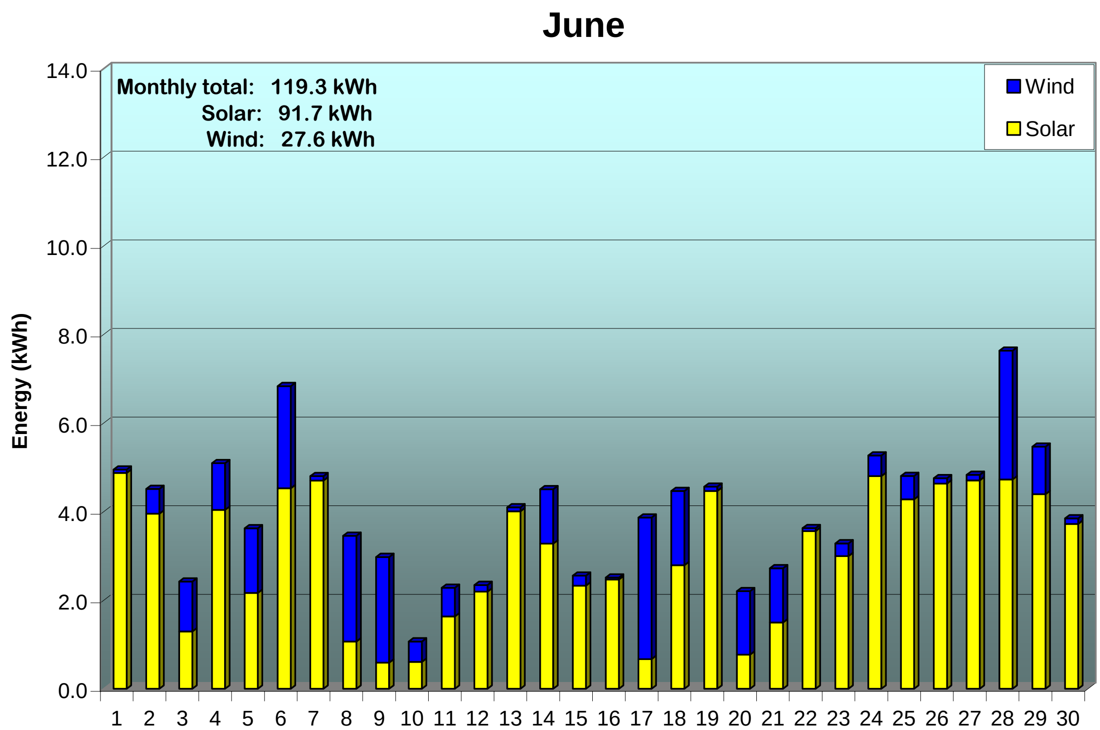


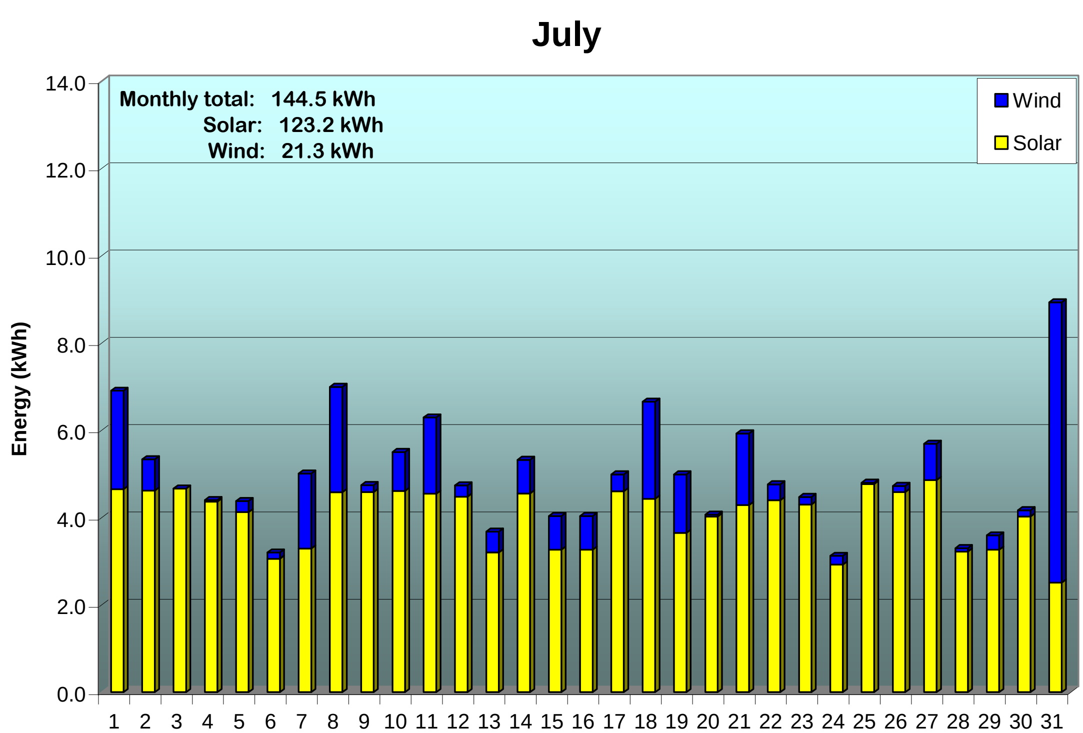

February
Monthly total: 124.8 kWh
Solar: 65.4 kWh
Wind: 59.4 KWh
Wind
Solar
Energy (kWh)
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28

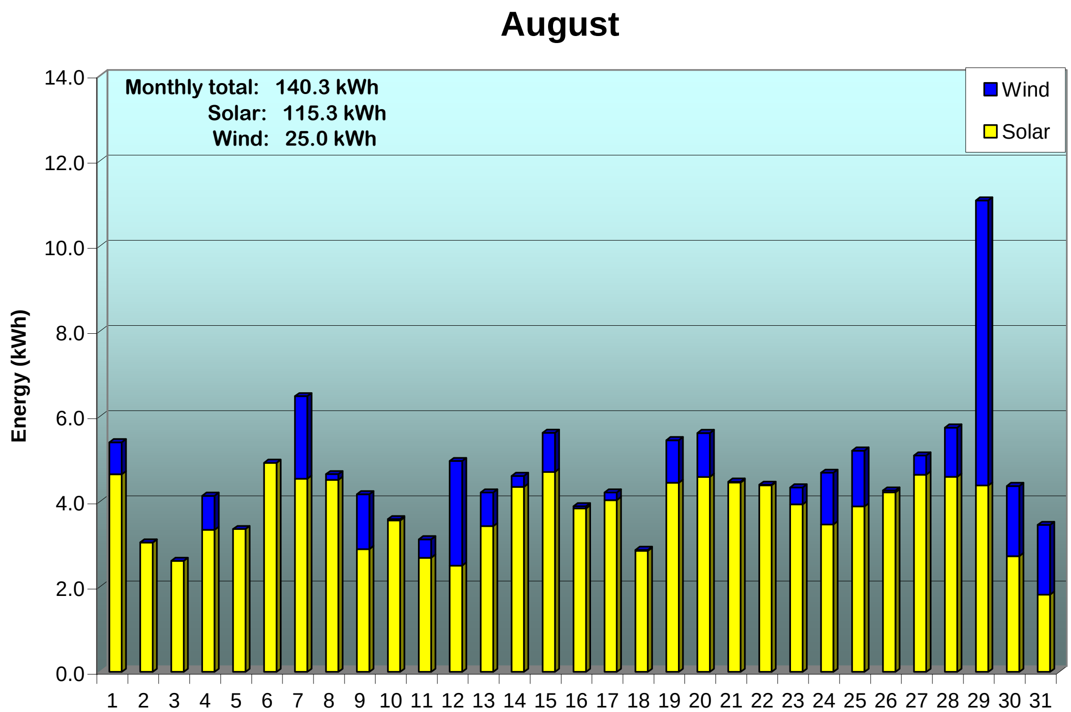

March
Monthly total: 142.6 kWh
Solar: 101.8 kWh
Wind: 40.8 kWh
Wind
Solar
Energy (kWh)
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31

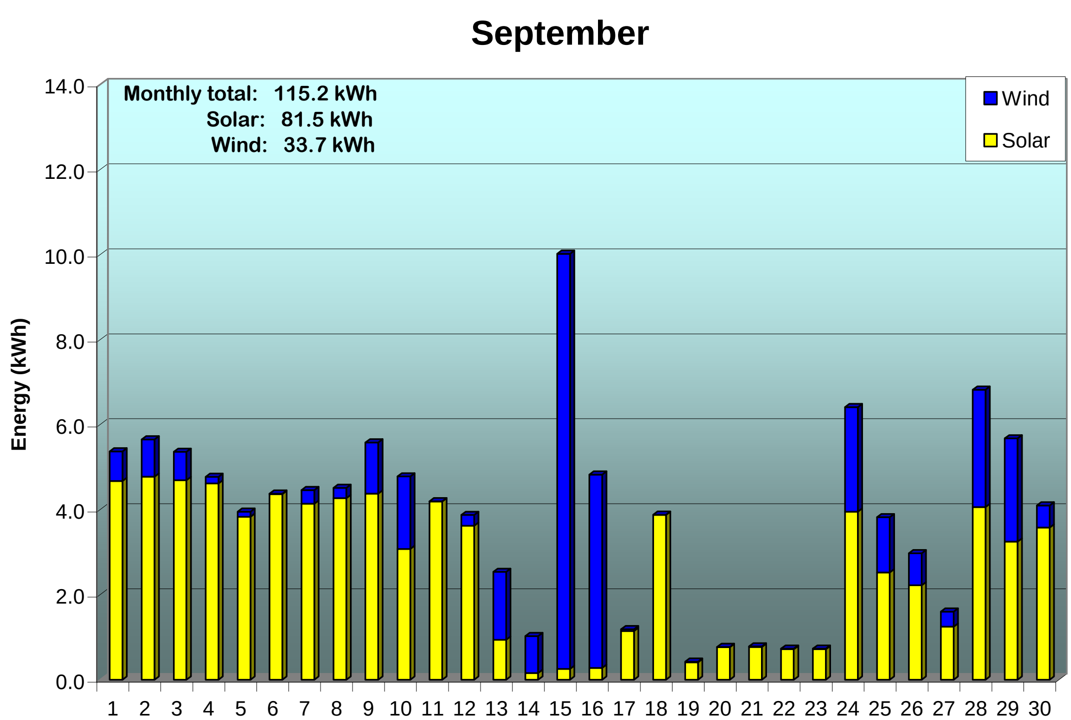

April
Monthly total: 152.4 kWh
Solar: 113.7 kWh
Wind: 38.7 kWh
Wind
Solar
Energy (kWh)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30

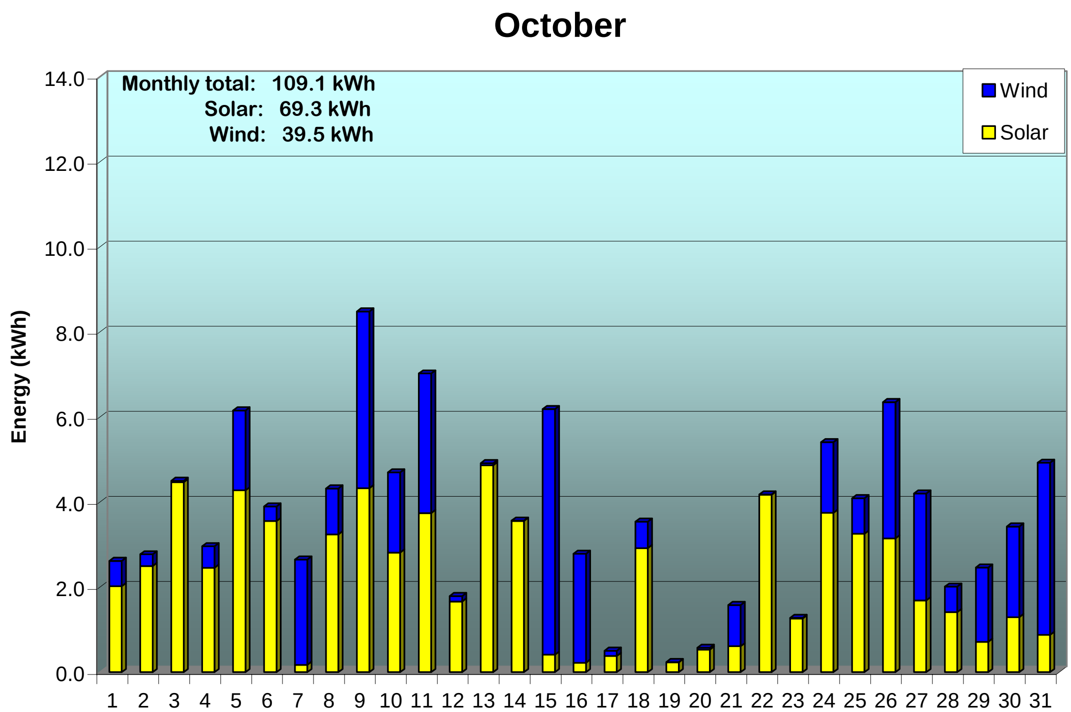

May
Monthly total: 143.7 kWh
Solar: 93.6 kWh
Wind: 50.1 kWh
Wind
Solar
Energy (kWh)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30

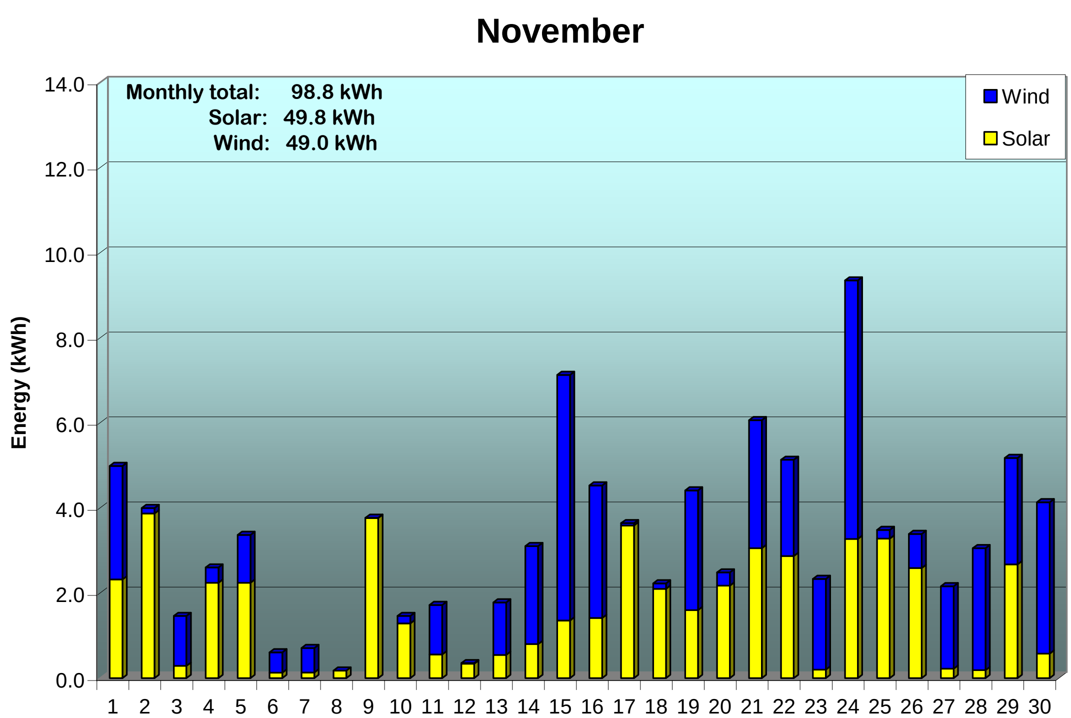

June
Monthly total: 119.3 kWh
Solar: 91.7 kWh
Wind: 27.6 kWh
Wind
Solar
Energy (kWh)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30

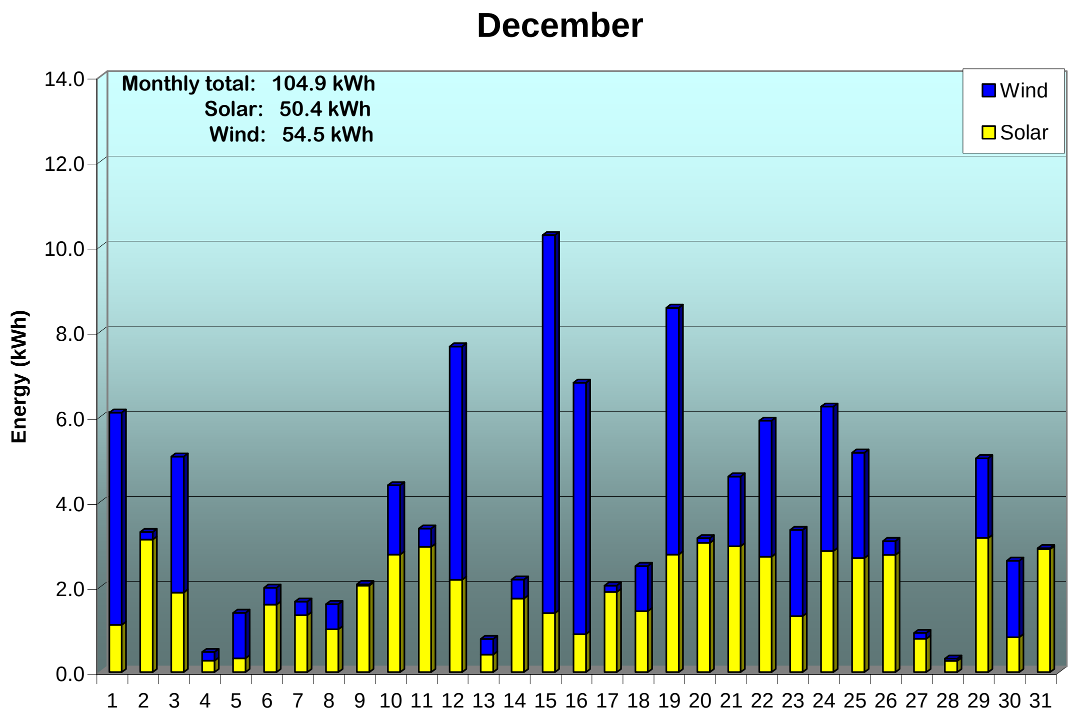

July
Monthly total: 144.5 kWh
Solar: 123.2 kWh
Wind: 21.3 kWh
Wind
Solar
Energy (kWh)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31


August
Monthly total: 140.3 kWh
Solar: 115.3 kWh
Wind: 25.0 kWh
Wind
Solar
Energy (kWh)
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31


September
Monthly total: 115.2 kWh
Solar: 81.5 kWh
Wind: 33.7 kWh
Wind
Solar
Energy (kWh)
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30


October
Monthly total: 109.1 kWh
Solar: 69.3 kWh
Wind: 39.5 kWh
Wind
Solar
Energy (kWh)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31


November
Monthly total: 98.8 kWh
Solar: 49.8 kWh
Wind: 49.0 kWh
Wind
Solar
Energy (kWh)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30



December
Monthly total: 104.9 kWh
Solar: 50.4 kWh
Wind: 54.5 kWh
Wind
Solar
Energy (kWh)
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31